

Calibration and validation of a model for simulating thermal and electric performance of an internal combustion engine-based micro-cogeneration device

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ABSTRACT

The growing worldwide demand for more efficient and less polluting forms of energy production has led to a renewed interest in the use of micro-cogeneration technologies in the residential. Among the others technologies, internal combustion engine-based micro-cogeneration devices are a market-ready technology gaining an increasing appeal thanks to their high efficiency, fuel flexibility, low emissions, low noise and vibration.

In order to explore and assess the feasibility of using internal combustion engine-based cogeneration systems in the residential sector, an accurate and practical simulation model that can be used to conduct sensitivity and what-if analyses is needed. A residential cogeneration device model has been developed within IEA/ECBCS Annex 42 and implemented into a number of building simulation programs. This model is potentially able to accurately predict the thermal and electrical outputs of the residential cogeneration devices, but it relies almost entirely on empirical data because the model specification uses experimental measurements contained within a performance map to represent the device specific performance characteristics coupled with thermally massive elements to characterize the device's dynamic thermal performance.

At the Built Environment Control Laboratory of Seconda Università degli studi di Napoli, an AISIN SEIKI micro-cogeneration device based on natural gas fuelled reciprocating internal combustion engine is available. This unit has been intensively tested in order to calibrate and validate the Annex 42 model. This paper shows in detail the series of experiments conducted for the calibration activity and examines the validity of this model by contrasting simulation predictions to measurements derived by operating the system in electric load following control strategy. The statistical comparison was made both for the whole database and the segregated data by system mode operation.

The good agreement found in the predictions of net electric power production, useful thermal output and primary power consumption allowed to conclude that the Annex 42 model can be used to carry out a detailed performance assessment in order to examine the applicability of the AISIN SEIKI unit for supplying building electrical and thermal energy requirements according to different load profiles during annual or multi-year operation.

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1. Introduction

Micro-cogeneration is the concurrent production of electricity and heat from a single fuel source with electrical output less than 50 kW [1]. There are several technologies being developed for micro-cogeneration including: a) reciprocating internal combustion engine-based cogeneration systems, b) micro-turbine based cogeneration systems, c) fuel cell-based cogeneration systems, d) reciprocating external combustion Stirling engine-based cogeneration systems.

Reciprocating internal combustion engine-based cogeneration systems are usually the prime mover of choice for small scale cogeneration applications [2]. This is attributed to their well-proven technology, robust nature, and reliability. However, they need regular maintenance and servicing to ensure availability. They are available over a wide range of sizes ranging from a few kilowatts to more than 10 MW, and can be fired on a broad variety of fuels with excellent availability [3], making them suitable for numerous cogeneration applications in residential, commercial, institutional and small scale industrial loads.

Micro-cogeneration has significant market potential. The MicroMap project reported that in Europe between 5 million and 12.5 million dwellings could have MCHP systems installed by 2020

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[4]. The larger and mini systems, for industrial application and for use in small organisations such as hospitals, schools and community centres or grouped households, have got proven track records. Micro-cogeneration systems are especially interesting for market of Small Family Houses (SFH) and Medium Family Houses (MFH), small buildings and small and medium scale enterprises (SME) [5]. These systems are even more attractive for remote communities where lack of central generation stations and costly connection to the grid is neither an affordable nor a preferable option [6]. However MCHP devices applicable to domestic users in individual households still need further development to be widely acceptable. Many scientific works [6–11] demonstrated that the micro-cogeneration technology has the potential, if designed and operated correctly, to reduce primary energy consumption and greenhouse gas emissions; reductions in combustion by-products such as nitrogen oxides, sulphur dioxide, and hydrocarbons are also a possibility [12,13]. In addition, micro-cogeneration can be economically attractive [14], and, thanks to its distributed nature, may help to improve reliability and security of local and national electricity supply [15,16]. Besides thermal energy recovered from small cogeneration plant can be used during the summer for the regeneration of a desiccant wheel, as well as for the operation of an absorption/adsorption heat pump [17–23].

The European Union is encouraging micro-cogeneration systems deployment to able meet international and domestic targets on carbon emissions: in the Directive 2004/8/EC of the European Parliament and of the Council [1] it is addressed the need to promote MCHP systems to saving primary energy, avoiding network losses and reducing emissions, in particular of greenhouse gases. In addition, in this directive it is stated that efficient use of energy by cogeneration can also contribute positively to the security of energy supply and to the competitive situation of the European Union and its Member States.

Even if micro-cogeneration is gaining more and more interest in the scientific community, the opportunity to use micro-cogeneration systems depends strongly on factors such as heat and power demand variations, control modes, the capacity and efficiency of the residential cogeneration system, and electricity import/export conditions and modes. Taking into account that the decision whether or not to install small cogeneration units for residential purposes also depends on economic considerations, government grants are also considered in order to bridge the economic barrier. Examples of such policy initiatives include the “Carbon Emissions Reduction Target (CERT)” in the United Kingdom [24] and the “Housing, Environment and Growth” initiative in Germany [25]. Therefore the feasibility of a micro-cogeneration system is a function of the design and size of the system as well as the building it is intended for. For this reason, an accurate and practical simulation model of micro-cogeneration devices is needed as a techno-economic analysis tool for studying and evaluating the performance of different systems in different load environments. Recently Voorspools and D'haeseleer [26], Hae-seldonckx et al. [27] and Onovwiona et al. [28] proposed simple empirical models to simulate the performance of SE and ICE units in building-integrated cogeneration applications. All three of these models are parametric in nature, and all are closely based on empirical data collected for specific cogeneration devices. These models are well-suited for use in building simulation and designed to predict system fuel use, power generation, and thermal output in response to part load ratio. However all three were derived directly from the performance data of specific systems, and cannot be readily recalibrated for study of other cogeneration products [29]. Recognizing the importance of study micro-cogeneration systems, the International Energy Agency approved the formulation of a new research annex (Annex 42) under the Energy conservation in Builds

and Community Systems (ECBCS) implementing agreement. The objectives of Annex 42 were to develop simulation models that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental, and economic performance of the technologies. As result of Annex 42 research activities, two generic models that characterize the performance of micro-cogeneration devices were developed: one for fuel cell-based cogeneration systems (SOFC and PEMFC) and a second one for combustion-based systems (SE and ICE). The Annex 42 combustion models rely extensively on parametric equations describing the relationships between key input and output parameters. Each of these parametric equations requires empirical constants that characterize aspects of the performance of specific cogeneration devices. The main requirement for the models was to accurately predict the thermal and electrical outputs from specific residential cogeneration devices. The specification of this model is detailed in Refs. [29,30]. Like previous models [26–28], the Annex 42 model [29,30] is empirical in nature, but it was also designed to support calibration with the measurements available during third-party testing of these devices. Instances of Annex 42 model were independently implemented into source code for four widely used building simulation tools (ESP-r [31], EnergyPlus [32], TRNSYS [33], and IDA-ICE [34]).

Several Annex 42 participants conducted experiments with prototype or early-market residential combustion-based cogeneration devices [35], but not all of the data produced in the Annex 42 were used to calibrate the models because some data were judged to be unsuitable for the Annex 42 models. Finally a detailed calibration and validation exercise was undertaken in Annex 42 just for one fuel cell-based cogeneration system (SOFC device [36,37]), and two combustion-based cogeneration systems (WhisperGen SE device [38,39] and Senertec ICE device [35,40]).

Therefore it is apparent from that few existing datasets had data suitable for combustion model calibration purposes. As a consequence, as highlighted in the final report of Annex 42 [35], it is extremely important that additional experimental data will be collected in order to:

- 1) predict the electric and thermal performances of other types of MCHP systems (each set of empirically derived model inputs is applicable to only one engine type, capacity, and fuel type and therefore re-calibration is required for each specific cogeneration system type);
- 2) improve critical aspects of the model, such as the start-up and shut-down phases of SE and ICE systems;
- 3) include additional governing physics and chemistry to improve understanding and enable the more accurate modelling of systems.

The present work describes a new experimental data set that was collected with the aim of calibrating and validating the Annex 42 combustion-based cogeneration model. Experiments were conducted on an AISIN SEIKI reciprocating internal combustion engine-based micro-cogeneration device fuelled by natural gas [41] available at the Built Environment Control Laboratory of Seconda Università degli Studi di Napoli. Differently from Senertec ICE device [40] (5.5 kW nominal electrical output and 12.5 kW nominal thermal output) that cannot modulate its output (other than turning on or off), AISIN SEIKI unit (6.0 kW nominal electrical output and 11.7 kW nominal thermal output) can modulate the electric power according to the electric requirement of the end-user. Several tests were carried out on this device under varied and controlled boundary conditions in order to generate a data set comprising of both steady-state and transient modes of operation. Measurements of the device's primary power consumption, electric

power production, thermal output, etc., under these operating conditions were measured and used to calibrate the various aspects of the model. Additional experiments were performed with different combinations of boundary conditions in order to validate the calibrated Annex 42 model. Specific limitations of the Annex 42 model for the treatment of steady-state, start-up, and shut-down sequences of operation are also highlighted here. The result of this work is a calibrated model that can accurately simulate the thermal and electrical performance of this ICE based micro-cogeneration device when coupled to a house's thermal plant.

In the next sections, a brief description of pertinent aspects of the combustion-based mathematical Annex 42 model is first provided, followed by a detailed presentation of the experimental set-up. The majority of the paper is dedicated to the illustration of the calibration procedures and to the comparisons among simulations conducted with the calibrated model and measurements from the validation experiment.

2. Model description

A combustion-based cogeneration device model has been developed within IEA/ECBCS Annex 42 for use within whole building simulation programs. The main objective of the model developed within Annex 42 is to accurately predict the thermal and electrical outputs of any combustion-based cogeneration systems and their explicit interaction with the building's envelope, thermal plant, and electrical systems.

The operation of the model requires as inputs 103 empirically derived coefficients. Therefore the model must be calibrated using empirical data and each set of model inputs is applicable to only one engine type, capacity, and fuel type.

In Table 1 the list of parameters to be calibrated is reported. The experimental procedure followed to establish each of the empirical constants reported in Table 1 (known as the process of model calibration) will be described in detail in the Section 4.

In addition to the calibration parameters specified in Table 1, the model requires as inputs also the parameters reported in Table 2. The input parameter fControl_signal (input number 2) allows to specify the interface to the high-level control modules. The model specification provides two interfaces to the high-level control modules, permitting them to set the MCHP system operating point without knowledge of the configuration or operation of the device. The two interfaces proposed are:

- a dimensionless control signal interface (input number 2 equal to the value 1): the controller will provide the dimensionless control signal interface with a coefficient u that varies between 0 and 1. The model will map this signal according to the following equation:

$$P_{\text{net}} = P_{\text{net,min}} + u \cdot (P_{\text{net,max}} - P_{\text{net,min}}) \quad (1)$$

where $P_{\text{net,min}}$ is the minimum electric output, $P_{\text{net,max}}$ is the maximum electric output and P_{net} is the net electric output of the unit. Based on Eq. (1) the system's maximum operation point is achieved when $u = 1$, and the minimum operating point is achieved when $u = 0$. Setting the parameter u equal to the value zero causes the system to be deactivated;

- an electrical control interface (input number 2 equal to the value 2): the controller will provide the electrical control interface with a desired electrical power flux P_{demand} . The CHP system model will determine the operating point corresponding to this power output;

In addition to the control signal, the controller should provide to the model a flag indicating if the unit should be activated, and which control interface is in use. This flag supports three states:

- deactivate the unit;
- activate the unit and use the electric load following interface;
- activate the unit and use the dimensionless load following interface.

The control flag is only necessary when both the dimensionless or electrical control signal interfaces are implemented. Implementations making exclusive use of either interface may choose to omit the control flag, and assume that the unit switches to standby when a control signal of zero (or less) is received. The flag is specified by the input parameter iControl_method.

The other three input parameters included in Table 2 represent, respectively, the room temperature T_{room} , the cooling water temperature entering the micro-cogeneration device $T_{\text{cw,i}}$ and the cooling water mass flow rate $\dot{m}_{\text{cw}}$.

Assigned both the calibration parameters and the input parameters, the model is able to provide as outputs the parameters described in Table 3.

Tables 1–3 include all calibration parameters, inputs and outputs in the order as they are used in the TRNSYS implementation of the Annex 42 ICE cogeneration device model. The variable names given here are those used in the code and the symbols used in the mentioned tables are those of the model specification.

In the following a brief description of the combustion mathematical Annex 42 model is reported.

The model comprises three basic control volumes:

- the energy conversion control volume represents the engine working fluid, combustion gases, and engine alternator;
- the engine thermal mass control volume represents the aggregate thermal mass of the engine block and most internal heat exchange equipment;
- the cooling water control volume represents the aggregate thermal mass of the cooling water and that portion of the heat exchanger in immediate thermal contact with the cooling fluid.

The energy and mass flows about these defined control volumes are depicted in Fig. 1.

The energy conversion control volume represents the conversion of the fuel's chemical energy to electricity and heat under steady conditions. The dynamic thermal response of the system is then characterized by both the engine thermal mass and the cooling water control volumes.

The net electrical output under steady conditions $P_{\text{net,ss}}$ and the thermal energy transferred to the engine thermal mass control volume under steady conditions $q_{\text{gen,ss}}$ are determined using overall conversion efficiencies that aggregate the effects of inefficiencies and auxiliary systems:

$$P_{\text{net,ss}} = \eta_e \cdot q_{\text{gross}} \quad (2)$$

$$q_{\text{gen,ss}} = \eta_q \cdot q_{\text{gross}} \quad (3)$$

$$q_{\text{gross}} = \dot{m}_{\text{fuel}} \cdot \text{LHV}_{\text{fuel}} \quad (4)$$

where η_e and η_q are, respectively, the steady-state part load electrical and thermal efficiencies, $\dot{m}_{\text{fuel}}$ is the fuel flow rate, and LHV_{fuel} is the lower heating value of the fuel.

In the Annex 42 model, the steady-state conversion efficiencies are represented as truncated tri-variate polynomial functions of

Table 1
Calibration parameters of the Annex 42 ICE cogeneration device model.

Number	Variable name	Description	Symbol	Unit
1	fPower_Out_MAX	System maximum power	$P_{net,max}$	W
2	fPower_Out_MIN	System minimum power	$P_{net,min}$	W
3	fCW_temperature_MAX	Maximum cooling water outlet temperature	—	°C
4	iFuel_type	1: Liquid 2: gaseous	—	—
5	fFuel_LHV	Liquid fuel lower heating value LHV	LHV_{fuel}	J/kg
6	fFuel_CO2_intensity	Liquid fuel CO ₂ factor	$\dot{m}_{fuel} / \sum \chi_i MM_i$	kgCO ₂ /kg _{fuel}
7	fFuel_composition(iHydrogen)	% hydrogen in fuel gas mixture	χ_i	mol/mol
8	fFuel_composition(iMethane)	% methane in fuel gas mixture	χ_i	mol/mol
9	fFuel_composition(iEthane)	% ethane in fuel gas mixture	χ_i	mol/mol
10	fFuel_composition(iPropane)	% propane in fuel gas mixture	χ_i	mol/mol
11	fFuel_composition(iButane)	% butane in fuel gas mixture	χ_i	mol/mol
12	fFuel_composition(iPentane)	% pentane in fuel gas mixture	χ_i	mol/mol
13	fFuel_composition(iHexane)	% hexane in fuel gas mixture	χ_i	mol/mol
14	fFuel_composition(iMethanol)	% methanol in fuel gas mixture	χ_i	mol/mol
15	fFuel_composition(iEthanol)	% ethanol in fuel gas mixture	χ_i	mol/mol
16	fFuel_composition(iC_Monoxide)	% CO in fuel gas mixture	χ_i	mol/mol
17	fFuel_composition(iC_Dioxide)	% CO ₂ in fuel gas mixture	χ_i	mol/mol
18	fFuel_composition(iNitrogen)	% nitrogen in fuel gas mixture	χ_i	mol/mol
19	fFuel_composition(iOxygen)	% oxygen in fuel gas mixture	χ_i	mol/mol
20	fFuel_Flow_Change_MAX	Maximum rate of change in fuel flow	$(d\dot{m}_{fuel}/dt)_{max}$	kg/s ²
21	fGross_Power_Change_MAX	Maximum rate of change in power output	$(dP_{net}/dt)_{max}$	W/s
22	fEffective_MC_engine	Power system thermal mass	$[MC]_{eng}$	J/K
23	fEffective_UA_HX	Effective heat recovery UA coefficient	$[UA]_{Hx}$	W/K
24	fEffective_UA_loss	Effective heat loss UA coefficient	$[UA]_{loss}$	W/K
25	fEffective_MC_HX	Heat exchanger thermal mass	$[MC]_{cw}$	J/K
26	fPeriod_duration	Start-up (warm-up) period duration	$t_{warm-up}$	s
27	fPeriod_duration(iOP_shutdown)	Cool-down period duration	$t_{cool-down}$	s
28	iCool-down_mode	Cool-down period mode (1: Mandatory, 2: optional)	—	—
29	fPeriod_AC_Power	Electric output at cool-down	$P_{net,cool-down}$	W
30	fPeriod_AC_Power	Net electrical output in standby mode	$P_{net,standby}$	W
31	fCorr_MIN_Power_OUT	Power output correlation minimum bound	—	W
32	fCorr_MAX_Power_OUT	Power output correlation maximum bound	—	W
33	fCorr_MIN_CW_temp	Cooling water temperature correlation minimum bound	—	°C
34	fCorr_MAX_CW_temp	Cooling water temperature correlation maximum bound	—	°C
35	fCorr_MIN_CW_flow	Cooling water flow correlation minimum bound	—	kg/s
36	fCorr_MAX_CW_flow	Cooling water flow correlation maximum bound	—	kg/s
37	fPM_elec_coeff	Coefficient	a_0	—
38	fPM_elec_coeff	Coefficient	a_1	—
39	fPM_elec_coeff	Coefficient	a_2	—
40–41	fPM_elec_coeff	Coefficient	a_3 – a_4	—
42	fPM_elec_coeff	Coefficient	a_5	—
43	fPM_elec_coeff	Coefficient	a_6	—
44–47	fPM_elec_coeff	Coefficient	a_7 – a_{10}	—
48	fPM_elec_coeff	Coefficient	a_{11}	—
49	fPM_elec_coeff	Coefficient	a_{12}	—
50	fPM_elec_coeff	Coefficient	a_{13}	—
51	fPM_elec_coeff	Coefficient	a_{14}	—
52–63	fPM_elec_coeff	Coefficient	a_{15} – a_{26}	—
64	fPM_ther_coeff	Coefficient	b_0	—
65	fPM_ther_coeff	Coefficient	b_1	—
66	fPM_ther_coeff	Coefficient	b_2	—
67–68	fPM_ther_coeff	Coefficient	b_3 – b_4	—
69	fPM_ther_coeff	Coefficient	b_5	—
70	fPM_ther_coeff	Coefficient	b_6	—
71–74	fPM_ther_coeff	Coefficient	b_7 – b_{10}	—
75	fPM_ther_coeff	Coefficient	b_{11}	—
76	fPM_ther_coeff	Coefficient	b_{12}	—
77	fPM_ther_coeff	Coefficient	b_{13}	—
78	fPM_ther_coeff	Coefficient	b_{14}	—
79–90	fPM_ther_coeff	Coefficient	b_{15} – b_{26}	—
91	iCW_Loop_configuration	Cooling water loop: pump configuration (1 = internal, 2 = external)	—	—
92–100	fPM_flow_coeff	Coefficient	c_0 – c_8	—
101–103	fPM_flow_coeff	Coefficient	d_0 – d_2	—

Table 2
Inputs of the Annex 42 ICE cogeneration device model.

Number	Variable name	Description	Symbol	Unit
1	iControl_method	Control method: 0 = deactivated 1 = dimensionless control 2 = power out control	—	—
2	fControl_signal	Control signal	—	—
3	fTemp_Room_F	Room air temperature	T_{room}	°C
4	fCW_temperature_in_F	Water temperature at HX inlet	$T_{\text{cw,i}}$	°C
5	fCW_mass_flow_F	Flow rate at HX inlet	$\dot{m}_{\text{cw}}$	kg/s

cooling water mass flow rate $\dot{m}_{\text{cw}}$, cooling water inlet temperature $T_{\text{cw,i}}$, and net electrical power output at steady-state $P_{\text{net,ss}}$:

$$\begin{aligned} \eta_e = & a_0 + a_1 P_{\text{net,ss}}^2 + a_2 P_{\text{net,ss}} + a_3 \dot{m}_{\text{cw}}^2 + a_4 \dot{m}_{\text{cw}} \\ & + a_5 T_{\text{cw,i}}^2 + a_6 T_{\text{cw,i}} + a_7 P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 + a_8 P_{\text{net,ss}} \dot{m}_{\text{cw}} \\ & + a_9 P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 + a_{10} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} + a_{11} P_{\text{net,ss}}^2 T_{\text{cw,i}}^2 \\ & + a_{12} P_{\text{net,ss}} T_{\text{cw,i}} + a_{13} P_{\text{net,ss}} T_{\text{cw,i}}^2 + a_{14} P_{\text{net,ss}}^2 T_{\text{cw,i}} \\ & + a_{15} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 + a_{16} \dot{m}_{\text{cw}} T_{\text{cw,i}} + a_{17} \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 \\ & + a_{18} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + a_{19} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 \\ & + a_{20} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + a_{21} P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 \\ & + a_{22} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 + a_{23} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} T_{\text{cw,i}} \\ & + a_{24} P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + a_{25} P_{\text{net,ss}} \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 \\ & + a_{26} P_{\text{net,ss}} \dot{m}_{\text{cw}} T_{\text{cw,i}} \end{aligned} \quad (5)$$

$$\begin{aligned} \eta_q = & b_0 + b_1 P_{\text{net,ss}}^2 + b_2 P_{\text{net,ss}} + b_3 \dot{m}_{\text{cw}}^2 + b_4 \dot{m}_{\text{cw}} \\ & + b_5 T_{\text{cw,i}}^2 + b_6 T_{\text{cw,i}} + b_7 P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 + b_8 P_{\text{net,ss}} \dot{m}_{\text{cw}} \\ & + b_9 P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 + b_{10} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} + b_{11} P_{\text{net,ss}}^2 T_{\text{cw,i}}^2 \\ & + b_{12} P_{\text{net,ss}} T_{\text{cw,i}} + b_{13} P_{\text{net,ss}} T_{\text{cw,i}}^2 + b_{14} P_{\text{net,ss}}^2 T_{\text{cw,i}} \\ & + b_{15} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 + b_{16} \dot{m}_{\text{cw}} T_{\text{cw,i}} + b_{17} \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 \\ & + b_{18} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + b_{19} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 \\ & + b_{20} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + b_{21} P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}}^2 \\ & + b_{22} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 + b_{23} P_{\text{net,ss}}^2 \dot{m}_{\text{cw}} T_{\text{cw,i}} \\ & + b_{24} P_{\text{net,ss}} \dot{m}_{\text{cw}}^2 T_{\text{cw,i}} + b_{25} P_{\text{net,ss}} \dot{m}_{\text{cw}} T_{\text{cw,i}}^2 \\ & + b_{26} P_{\text{net,ss}} \dot{m}_{\text{cw}} T_{\text{cw,i}} \end{aligned} \quad (6)$$

Table 3
Outputs of the Annex 42 ICE cogeneration device model.

Number	Variable name	Description	Symbol	Unit
1	Temp(1)	Temperature of the engines thermal mass control volume	T_{eng}	°C
2	Temp(2)	Exit temperature of the cooling water control volume	$T_{\text{cw,o}}$	°C
3	fReport_Net_Power	Steady-state electrical net power output	$P_{\text{net,ss}}$	W
4	fReport_Heat_Recovery	Steady-state heat generation	$q_{\text{gen,ss}}$	W
5	fReport_Fuel_Flow	Fuel flow	$\dot{m}_{\text{fuel}}$	kg/s
6	fReport_Fuel_LHV_rate	LHV flow rate	q_{gross}	W
7	fReport_Heat_Loss	Skin losses to the containment room	$q_{\text{skin-loss}}$	W
8	fReport_Heat_Transfer	Heat transferred to the cooling water	q_{HX}	W
9	fReport_Electric_efficiency	Electrical efficiency	η_e	—
10	fReport_Thermal_efficiency	Thermal efficiency	η_q	—
11	fReport_Cogen_efficiency	Total efficiency	$\eta_e + \eta_q$	—
12	fFuel_LHV	Lower heating value of the fuel	LHV_{fuel}	J/kg
13	fReport_Air_Flow	Air flow rate	$\dot{m}_{\text{air}}$	kg/s
14	Average_CO2_emissions	Average CO ₂ emissions	$\dot{m}_{\text{CO}_2}$	kg/s

where a_0 to a_{26} and b_0 to b_{26} are 54 empirically derived coefficients (calibration parameters 37–90) that characterize the conversion efficiencies.

In the Annex 42 model the composition of the gaseous fuels, is defined in terms of molar fractions (calibration parameters 7–19). The composition data is used to calculate the fuel LHV_{fuel}. As alternative, the model allows for a “generic liquid fuel”, whose empirically measured lower heating value (calibration parameter 5) and CO₂ emission factor (calibration parameter 6) are provided by the user; calibration parameter 4 allows to choose between gaseous and liquid fuel.

The efficiency correlations do not characterize the MCHP dynamic thermal or electrical behaviour. Due to the effects of thermal storage, heat losses and internal controls within the CHP system, the actual rates of power delivery and heat recovery (P_{net} and q_{HX}) may differ from the steady-state rates described in Eqs. (2) and (3).

The model assumes that the dynamic thermal behaviour of the combustion cogeneration device is attributable to the thermal mass of its engine block and encapsulated working fluid, internal heat exchange equipment represented by the thermal mass control volume. The thermal energy stored within this control volume is quantified using an aggregate thermal capacitance $[\text{MC}]_{\text{eng}}$ (calibration parameter 22) and an equivalent average engine temperature T_{eng} . In addition, the model assumes the heat transfer to the cooling water is proportional to the difference in the temperature of cooling water control volume and the engine control volume temperature; the heat transfer between the engine and the cooling water control volume is quantified as follows:

$$q_{\text{HX}} = [\text{UA}]_{\text{HX}} \cdot (T_{\text{eng}} - T_{\text{cw,o}}) \quad (7)$$

where $[\text{UA}]_{\text{HX}}$ (calibration parameter 23) is the overall thermal conductance between the engine cooling water control volumes, and $T_{\text{cw,o}}$ is the cooling water temperature exiting the micro-cogeneration device.

In the model it is also assumed that the heat lost from the engine is proportional to the temperature difference between the engine control volume and the surroundings:

$$q_{\text{loss}} = [\text{UA}]_{\text{loss}} \cdot (T_{\text{eng}} - T_{\text{room}}) \quad (8)$$

where $[\text{UA}]_{\text{loss}}$ (calibration parameter 24) is the effective thermal conductance between the engine control volume and the surroundings.

Consequently the engine and cooling water control volume energy balance equations can be written as follows:

$$\begin{aligned} [\text{MC}]_{\text{eng}} \cdot (dT_{\text{eng}}/dt) = & q_{\text{gen,ss}} - [\text{UA}]_{\text{HX}} \cdot (T_{\text{eng}} - T_{\text{cw,o}}) \\ & - [\text{UA}]_{\text{loss}} \cdot (T_{\text{eng}} - T_{\text{room}}) \end{aligned} \quad (9)$$

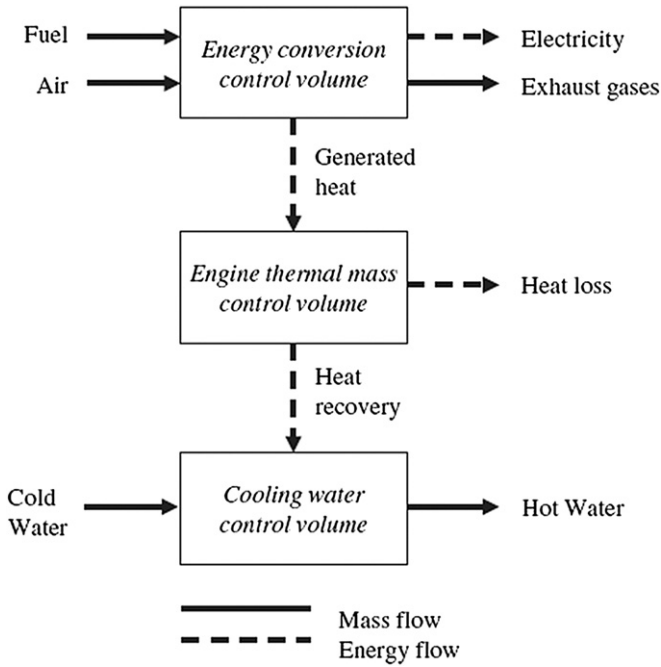


Fig. 1. Discretization scheme employed by Annex 42 model [39].

$$[MC]_{cw} \cdot (dT_{cw,o}/dt) = [UA]_{HX} \cdot (T_{eng} - T_{cw,o}) + [\dot{m}c_p]_{cw} \cdot (T_{cw,i} - T_{cw,o}) \quad (10)$$

where $[MC]_{cw}$ is the thermal capacitance of the encapsulated cooling water and heat exchanger shell in immediate thermal contact (calibration parameter 25), and $[\dot{m}c_p]_{cw}$ is the thermal capacity flow rate associated with the cooling water.

Within the model, low-level controls manage the operation of subsystems within the unit to achieve optimum (and safe) performance for a given operating point. These controls can restrict the rates at which the power output and fuel flowing to the system can be increased or decreased.

The Annex 42 model allows constraints on the maximum rate of change permitted in the system fuel flow using empirically derived data as follows:

$$d\dot{m}_{fuel}/dt = \left| \dot{m}_{fuel,demand}^{t+\Delta t} - \dot{m}_{fuel}^t \right| / \Delta t \quad (11)$$

where $\dot{m}_{fuel,demand}^{t+\Delta t}$ is the system fuel flow rate requested by a high-level control, t is time and Δt is the duration of the simulation time step. The fuel flow rate requested from the MCHP unit can then be adjusted to reflect the unit's embedded internal controller characteristics:

$$\dot{m}_{fuel}^{t+\Delta t} = \begin{cases} \dot{m}_{fuel,demand}^{t+\Delta t} & \text{if } d\dot{m}_{fuel}/dt \leq (d\dot{m}_{fuel}/dt)_{max} \\ \dot{m}_{fuel}^t \pm (d\dot{m}_{fuel}/dt)_{max} & \text{if } d\dot{m}_{fuel}/dt > (d\dot{m}_{fuel}/dt)_{max} \end{cases} \quad (12)$$

where $\dot{m}_{fuel}^t \pm (d\dot{m}_{fuel}/dt)_{max}$ is the maximum rate of change in the system fuel flow rate permitted by the low-level controller.

The user may optionally constrain the unit's predicted dynamic electric response using empirical data. Changes in the system's electrical output can be described using a linear derivative:

$$dP_{net}/dt = \left| P_{net}^{t+\Delta t} - P_{net}^t \right| / \Delta t \quad (13)$$

where P_{net} is the system's power delivery under steady-state conditions. The rate of change in the CHP system's power output is compared to the maximum rate of change derived from empirical data, and adjusted to reflect the unit's transient characteristics:

$$P_{net}^{t+\Delta t} = \begin{cases} P_{net}^{t+\Delta t} & \text{if } dP_{net}/dt \leq (dP_{net}/dt)_{max} \\ P_{net}^t \pm (dP_{net}/dt)_{max} & \text{if } dP_{net}/dt > (dP_{net}/dt)_{max} \end{cases} \quad (14)$$

where $P_{net}^t \pm (dP_{net}/dt)_{max}$ is the maximum rate of change in the system's electrical output.

Eq. (11) defines the calibration parameter 20, while Eq. (13) defines the calibration parameter 21.

The model also includes an overheat-protection control that deactivates the unit when the coolant outlet temperature exceeds a specified value (calibration parameter 3).

Typically, a MCHP system will produce heat and power when in normal operation mode. However, MCHP systems may exhibit three other operating modes with markedly different characteristics; these are the standby, warm-up and cool-down modes of operation. The model tracks which operating mode the MCHP unit is currently in and switches the unit between modes depending on the prevailing system state, low-level control signals and system boundary conditions.

In the Annex 42 micro-cogenerator model, the warm-up is the period during which there is a static time delay between activation of the unit and electrical power generation.

The power generated by these devices is determined as:

$$P_{net,warm-up} = \begin{cases} 0 & \text{if } (t - t_0) < t_{warm-up} \\ P_{demand} & \text{if } (t - t_0) \geq t_{warm-up} \end{cases} \quad (15)$$

where t is the current time and t_0 is the time at which the engine was started. The value of $t_{warm-up}$ (calibration parameter 26) describes the warm-up duration. The model assumes that the warm-up characteristics of internal combustion engines are not sensitive to engine temperature.

During cool-down, the engine is assumed to consume no fuel and generate no heat, even if auxiliary electrical systems in the engine may require additional power to complete the shut-down. Thus during cool-down the model assumes:

$$P_{net} = P_{net,cool-down} \quad (16)$$

$$q_{gen} = 0 \quad (17)$$

$$\dot{m}_{fuel} = 0 \quad (18)$$

where $P_{net,cool-down}$ (calibration parameter 29) is the power used by the unit's control systems while in cool-down operation. The user prescribes a cool-down time $t_{cool-down}$ (calibration parameter 27) defining the duration of the cool-down period.

When no electric or thermal output is requested, the unit is assumed to be in standby mode. During standby operation, the model assumes that unit consumes no fuel and produces no heat. However, the electronic controllers within the unit require some electricity while awaiting activation. Thus:

$$P_{net} = P_{net,standby} \quad (19)$$

$$q_{gen} = 0 \quad (20)$$

$$\dot{m}_{fuel} = 0 \quad (21)$$

where $P_{net,standby}$ (calibration parameter 30) is the power used by the unit's control systems while in standby operation.

3. Experimental set-up and measurement procedures

A schematic diagram of the test apparatus of the Built Environment Control Laboratory of Seconda Università degli studi di Napoli detailing instrumentation components is shown in Fig. 2. The experimental set-up is located in Frignano, a municipality in the Province of Caserta (around 20 km far from Naples).

The micro-cogenerator is the model GECC60A2 NR/P produced by AISIN SEIKI. This model is based on a natural gas fuelled reciprocating internal combustion engine and the engine has three cylinders with four strokes and a total displacement of 952 cm³. The unit can modulate the electric power according to the electric load required by the end-user. The electric demand profile can be varied by using eight halogen lamps; each lamp is equipped with a timer by means of which it is possible to schedule the switching on and the switching off of each lamp. As alternative, the micro-cogenerator can operate in order to follow the electric needs of the building for lighting and the operation of PCs, printers, plotters, etc. In this configuration, the unit is connected in parallel to the electric grid.

The thermal recovery during plant operation is obtained from the exhaust gases and the engine jacket of the micro-cogenerator by using a water–glycol mixture as coolant. The heat recovered by the water–glycol mixture is transferred to the cold water flowing in a Plate Heat Exchanger (PHE). The cold water is circulated by the wet rotor pump P1 and its mass flow rate can be modified by varying the pump revolution speed: three different values (950, 1300, and 1850 rpm) can be manually set. The thermal power absorbed by the cold water is stored in an internal heat exchanger equipped 1000 dm³ tank. The hot water storage is insulated with 50 mm flexible polyurethane layer and is furthermore equipped with an auxiliary 4.0 kW electric resistance fed by the micro-cogenerator. During the winter the thermal energy stored in the tank is used for heating a part of the entire building: the hot water in the storage tank is circulated into three fan-coils by using the wet rotor pump P2, while during the warm season the recovered thermal energy is supplied to a triple-state water–LiCl absorption system.

As above-mentioned the micro-cogenerator can follow the electric load, but, as alternative, it can operate according to an external temperature signal coming from a thermostat located on the recovery tank: when this temperature exceeds a fixed value, the prime mover stops the thermal recovery (thermal energy produced by the prime mover is dissipated into the ambient) and supplies electric energy only. Thermal energy dissipation should be strictly avoided, as it represents a condition in which the cogenerated

thermal energy would not be effectively used, and this often undermines the benefits of combined electrical and thermal “production”.

During the winter the thermal energy stored is used for heating a part of the entire building: the hot water in the storage tank is circulated into three fan-coils by using the wet rotor pump P2. The thermal power supplied for heating can be varied by modifying the pump revolution speed (three different values are possible: 1688, 2374, 2683 rpm) and/or by-passing one or more fan-coils and/or by selecting the blower velocity of each fan-coil.

The cogeneration system has an internal control to keep the internal water–glycol temperature lower than a fixed value in order to prevent conditions endangering the engine block and it is not possible to influence this temperature hold control from external during the test: the unit controls the water–glycol temperature by-passing totally or partially the water–glycol mass flow rate into the radiator and activates the radiator fan when the water–glycol temperature reaches a specific high value (around 70 °C); the unit decides how much water–glycol mass flow rate must be by-passed into the radiator and the radiator fan activation depending on the water–glycol temperature at the inlet of the plate heat exchanger.

The experimental plant is well instrumented in order to measure directly the following parameters:

- water temperature in the key-points of the plant;
- ambient temperature;
- water mass flow rate in the key-points of the plant;
- natural gas mass flow rate entering the micro-cogenerator;
- electric power required by the lamps;
- electric power supplied by the micro-cogenerator to the end-user.

Water and ambient temperatures are measured by using resistance thermometers Pt100; water mass flow rate is obtained by using an ultrasonic mass flow sensor, while a thermal mass flow metre is installed to evaluate the natural gas volumetric flow rate; two watt-metres measure the electric power supplied by micro-cogenerator and the electric power requested to the MCHP system. Two resistance thermometers were constructed to measure a temperature profile within the hot water tank.

The quantities directly measured during the experiments and the instrumentation employed are provided in Table 4. The instrumentation bias errors associated with each measurement are also given in Table 4.

The signals coming from the resistance thermometers Pt100 are acquired by three cFP-RTD-124 analogue input modules (produced by National Instruments®), while the signals coming from the other sensors are managed by two cFP-AI-110 analogue input modules (produced by National Instruments®). Each acquisition device is a 16-bit resolution system with eight current outputs (4 ÷ 20 mA). The digital data coming from the modules are sent to a personal computer. The software LabView 8.0 is used to define the acquisition frequency and to monitor and/or record all the directly measured and calculated parameters.

Each quantity was measured and logged at 1 s intervals.

The micro-cogeneration device's commissioning software GECCON allows to record additional intrusive measurements including temperature of water–glycol mixture exiting and entering engine, ambient temperature, engine revolution speed, thermal output, electrical output, radiator fan activation, etc.

4. Model calibration

As discussed above, the Annex 42 model was developed using a “grey box” approach, wherein the structure of the model is

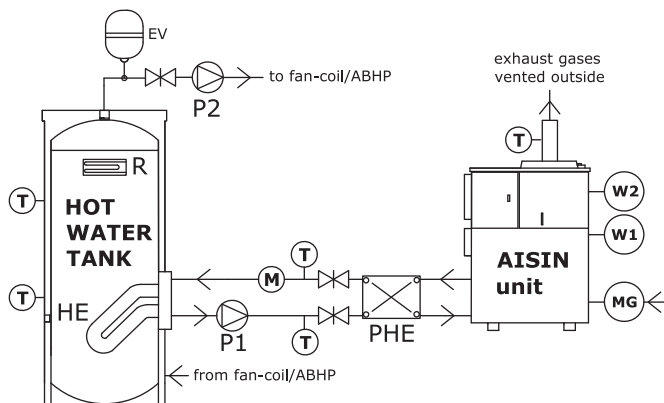


Fig. 2. Scheme of experimental apparatus (T: resistance thermometer; M: cooling water volumetric flow meter; W: Wattmeter; MG: natural gas volumetric flow meter; P: variable speed driven Pump; PHE: Plate Heat Exchanger; HE: internal Heat Exchanger; EV: Expansion Vessel; R: electric Resistance; ABHP: ABsorption Heat Pump).

Table 4
Measured quantities and instrumentation.

Parameter	Symbol	Unit	Instrument	Range	Instrumentation bias error
Volumetric fuel flow rate	$\dot{m}_{\text{fuel}}$	Nm ³ /h	Thermal volumetric flow meter	0 ÷ 5.0 Nm ³ /h	±0.8% of reading ±0.2% of full scale
Volumetric cooling water flow rate	$\dot{m}_{\text{cw}}$	l/min	Ultrasonic mass flow meter	0 ÷ 50 l/min	±2.5% of full scale
Temperature of exhaust gas	T_{exh}	°C	Resistance thermometer Pt100	−50 ÷ 200 °C	±0.2 °C
Temperature of coolant exiting engine	$T_{\text{cw,o}}$	°C	Resistance thermometer Pt100	−50 ÷ 80 °C	±0.2 °C
Temperature of coolant entering engine	$T_{\text{cw,i}}$	°C	Resistance thermometer Pt100	−50 ÷ 80 °C	±0.2 °C
Temperature of water in storage tank	$T_{\text{HWT},1}$	°C	Resistance thermometer Pt100	−50 ÷ 80 °C	±0.2 °C
	$T_{\text{HWT},2}$	°C			
Ambient air temperature	T_{room}	°C	Resistance thermometer Pt100	−50 ÷ 80 °C	±0.2 °C
Net DC electrical output	P_{net}	W	Wattmeter	0 ÷ 6 kW	0.2% of full scale
Electrical load	P_{demand}	W	Wattmeter	0 ÷ 10 kW	0.2% of full scale

roughly related to the basic underlying physical processes. However, many of the characteristic equations used in the model take the form of parametric equations describing the relationships between key input and output parameters. Each of these parametric equations requires the input of empirical constants that characterize the performance of subsystems of specific cogeneration devices.

This section describes the calibration of the Annex 42 combustion engine-based cogeneration model using experimental data from the AISIN SEIKI cogeneration unit described in Section 3.

A two-stage calibration process was adopted. Firstly, the equations describing the steady-state electrical and thermal efficiencies were formulated using data from testing the unit at different steady-state operating conditions. Secondly, the dynamic characteristics of the model were calibrated using data from the device in thermally transient modes of operation.

In 2004 Annex 42 participants defined an experimental protocol for testing cogeneration equipment. This protocol guided Annex 42 testing programs to ensure the resulting data were suitable for calibration and validation of the model. A detailed description of the protocol is reported in Ref. [38].

4.1. Static model calibration

In this section the calibration procedures followed to determine the calibration parameters 1–21, 26–30, 37–103 specified in Table 1 are described in detail.

4.1.1. Calibration parameter 1

Calibration parameter 1 (Table 1) represents the maximum electric power that can be provided by the MCHP. As above-mentioned the AISIN SEIKI unit is able to follow the electric load. A specific test has been carried in order to identify the calibration parameter 1: the results of this experiment is reported in Fig. 3 where the electric power provided by the MCHP during normal mode operation is plotted against the lapsed time spent in operation, while the electric load applied to the MCHP itself is around 6.8 kW. Fig. 3 shows that the power generation remains relatively constant and lower than the required electric load: the average observed power produced by the unit during 8000 s of operation is 5584.4 W. Therefore, the model's maximum power generation parameter ($P_{\text{net,max}}$) is set to 5596.2 W. Regarding this point it can be noticed that, as above-mentioned, the cogeneration system has an internal control to keep the internal water–glycol temperature

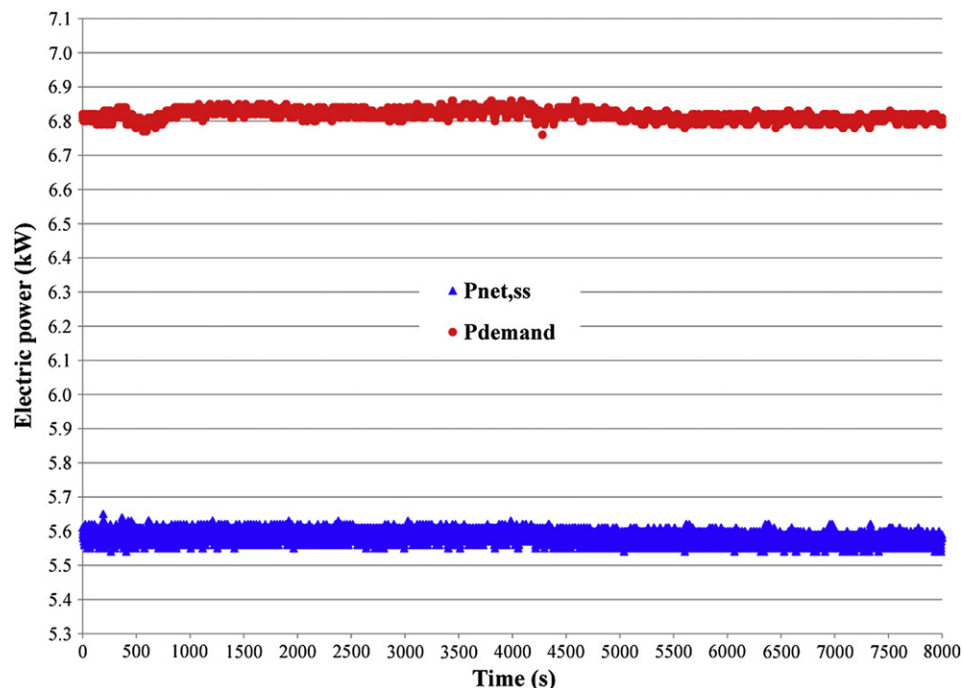


Fig. 3. $P_{\text{net,ss}}$ and P_{demand} as a function of time during normal mode operation.

lower than a fixed value in order to prevent conditions endangering the engine block. When the water–glycol temperature reaches a specific high value (around 70 °C), the unit activates the radiator fan activation: in case of the radiator fan is activated while the unit is not providing its maximum electrical output, then the unit internal control increases the engine revolution speed and therefore the net electrical output does not change; in case of the radiator fan is activated while the unit is providing its maximum electrical output ($P_{\text{net,ss}} = P_{\text{net,max}}$), then $P_{\text{net,ss}}$ reduces (becoming around 150 W lower) due to the fan electric consumption: however this net electric output reduction cannot be taken into account by the Annex 42 model (an external control is needed).

4.1.2. Calibration parameter 2

The value of calibration parameter 2 (Table 1) depends on the value of input number 1 (Table 2): in case of a dimensionless control signal interface is used (input number 1 equal to the value 1), calibration parameter 2 is the coefficient u reported in Eq. (1); in case of an electrical control interface is used (input number 1 equal to the value 2), the MCHP system model will determine the unit operating point corresponding to the desired electrical power flux P_{demand} and the value of calibration parameter 2 represents the minimum electric output of the unit. In this work, input number 1 is set to 2 and calibration parameter 2 is set to 0.

4.1.3. Calibration parameter 3

Calibration parameter 3 defines the maximum cooling water outlet temperature: the model shuts down the unit in case of the cooling water temperature at the outlet of the system exceeds the value set for the calibration parameter 3. However the AISIN SEIKI cogeneration device analysed in this work is not deactivated in any case and so it is not turned off when the cooling water temperature reaches a specific value. As a consequence, the control associated to the parameter 3 is disabled.

4.1.4. Calibration parameters 4–19

Calibration parameter 4 identifies the fuel type (liquid or gaseous). In case of a liquid fuel is utilized, the model requires the specification of an empirically derived lower heating value (calibration parameter 5) and the liquid fuel CO₂ emission factor (calibration parameter 6); AISIN SEIKI unit is fuelled by natural gas: in this case the model requires just the composition of the fuel by setting the calibration parameters 7–19.

SUN facility is not equipped to measure the composition or calorific heating value of the natural gas used to fuel the AISIN SEIKI cogeneration device. As a consequence, the natural gas composition presented in Table 5 [42] is assumed for the Annex 42 model calibration work.

Table 5
Assumed natural gas composition.

Compound	Molar mass (g/mol)	Mole fraction [%]
Hydrogen	2.016	0
Methane	16.043	99.461
Ethane	30.07	0.063
Propane	44.097	0.009
Butane	58.123	0.008
Pentane	72.15	0
Hexane	86.18	0.01
Methanol	32.042	0
Ethanol	46.07	0
Carbon monoxide	28.01	0
Carbon dioxide	44.01	0.03
Nitrogen	28.014	0.419
Oxygen	15.999	0

According to the specified composition, the model calculates the lower heating value and the CO₂ emission factor. According to the calculation method implemented in the model, the composition reported in Table 5 provides a lower heating value of 49,599 kJ/kg.

4.1.5. Calibration parameters 37–90

Calibration parameters 37–90 are the empirically derived coefficients that characterize the influence of cooling water mass flow rate $\dot{m}_{\text{cw}}$, cooling water inlet temperature $T_{\text{cw,i}}$, and net electrical power output at steady-state $P_{\text{net,ss}}$ on the steady-state conversion efficiencies (Eqs. (5) and (6)).

Algorithm calibration tests are specified in the experimental protocol defined by Annex 42 participants for testing cogeneration equipment [38] in order to identify calibration parameters 37–90. In particular, the protocol suggests to operate the cogeneration device with both a constant electrical output and a constant cooling mass flow rate while the temperature of the water supplied by the experimental facility to the cogeneration device's heat exchanger is varied over the range that can be achieved given the constraints of the experimental set-up and the operational requirements of the cogeneration device in approximately 5 °C steps; according to the protocol, the above test sequence should be repeated at other constant electrical outputs and then repeated one more time at other constant cooling water mass flow rates.

However the SUN test facility is designed to replicate real-world conditions inside a residential application and cannot impose steady-state conditions on the combustion cogeneration unit and so all of the experiments conducted at SUN were dynamic tests in which the temperature of the cooling water varied continuously according to conditions in the water tank. In Table 6 the operating conditions experimentally investigated at the Built Environment Control Laboratory of SUN in order to determine the parameters a_0 – a_{26} and b_0 – b_{26} are summarized: the date, the steady-state electric output, the cooling water flow rate, the minimum cooling water inlet temperature and the maximum cooling water inlet temperature are specified for each test.

As suggested by the protocol, the system was operated with three different electric outputs levels: ≈ 5.6 kW, ≈ 3.1 kW and ≈ 0.6 kW; tests number 1–3 have been performed with a cooling water flow rate of 0.29 l/s, while the remaining experiments have been carried by using a lower flow rate of the coolant equal to 0.18 l/s.

The set of six experiments provided a “performance map” of cogeneration device over the full range of system outputs and thermal boundary conditions and it has been carried out with the main aim to characterize the influence of the following parameters on both electric and thermal efficiencies:

- electrical power output;
- flow rate of water entering the micro-cogeneration device for thermal load extraction;
- temperature of water entering the micro-cogeneration device for thermal load extraction.

Table 6
Operating conditions during normal mode operation.

Test number	Date (day/month/year)	$P_{\text{net,ss}}$ (kW)	$\dot{m}_{\text{cw}}$ (l/s)	$T_{\text{cw,i,min}}$ (°C)	$T_{\text{cw,i,max}}$ (°C)
1	02/11/2011	5.58	0.29	24.2	62.0
2	11/11/2011	3.15	0.29	27.6	64.5
3	07/12/2011	0.60	0.29	21.0	56.0
4	08/11/2011	5.60	0.18	26.0	57.7
5	21/11/2011	3.13	0.18	22.9	61.7
6	25/11/2011	0.58	0.18	25.4	67.1

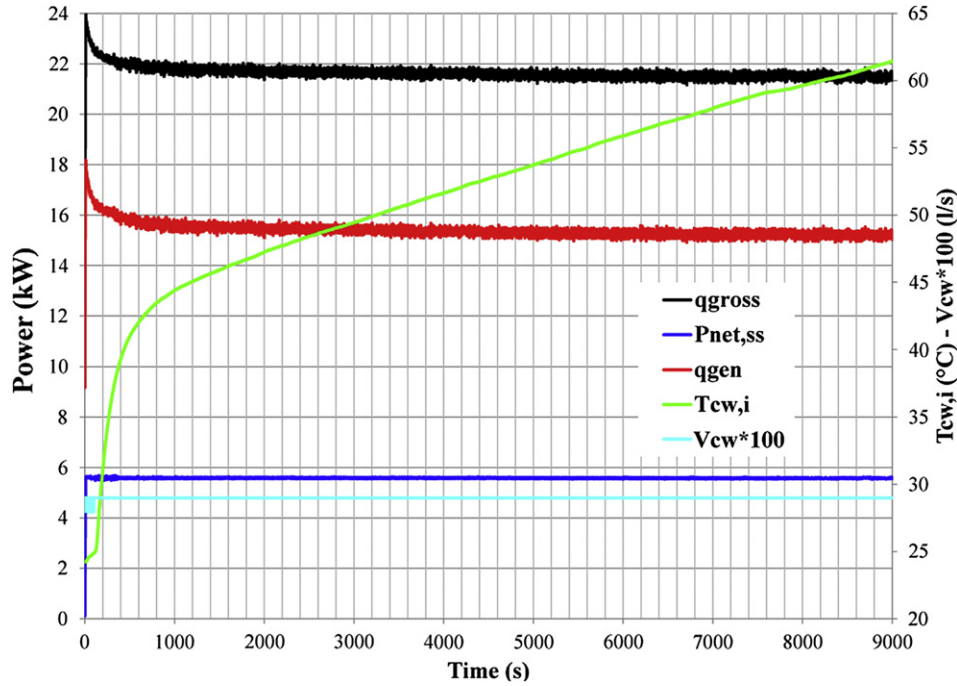


Fig. 4. System operation during test number 6.

The unit has been maintained switched off at least 72 h between two consecutively tests in order to evaluate system efficiency in case of cold start-up.

As example, in Fig. 4 the primary power q_{gross} , the net electric power provided by the MCHP system P_{net} , the recoverable heat q_{gen} , the cooling water flow rate $\dot{V}_{cw}$ and the temperature of water entering the cogenerator's heat exchanger $T_{cw,i}$ gathered during test number 6 (Table 6) are reported as a function of the time.

The data reported in this figure are referred to the system operation in "normal mode" before the activation of the emergency radiator fan.

The values of the parameters P_{net} , $\dot{V}_{cw}$ and $T_{cw,i}$ have been obtained by a direct measurement, while the evaluation of the parameters q_{gross} and q_{gen} was indirect. In particular, the primary power and the recoverable heat have been calculated as follows:

$$q_{gross} = \dot{V}_{fuel} \cdot \rho_{fuel} \cdot LHV_{fuel} \quad (22)$$

$$q_{gen} = q_{gross} - P_{net} - q_{exh} \quad (23)$$

where q_{exh} is the thermal power dissipated by the exhaust gases.

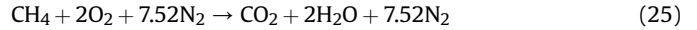
Eq. (23) has been derived from the energy balance on the energy conversion control volume (Fig. 1).

In Eq. (22) the fuel volumetric flow rate $\dot{V}_{fuel}$ is directly measured, the fuel density at normal conditions ρ_{fuel} is assumed equal to 0.719 kg/Nm³, the lower heating value of the fuel LHV_{fuel} is provided by the model accordingly with the fuel composition specified in Table 5 ($LHV_{fuel} = 49,599$ kJ/kg); the net electric power provided by the MCHP system P_{net} in the Eq. (23) is obtained by a direct measurement, while the thermal power dispersed by the exhaust gases is calculated by using the following formula:

$$q_{exh} = \dot{m}_{exh} \cdot c_{p,exh} \cdot (T_{exh} - T_{room}) \quad (24)$$

where $\dot{m}_{exh}$, $c_{p,exh}$ and T_{exh} are, respectively, the mass flow rate, the specific heat at constant pressure and the temperature of the exhaust gases and T_{room} is the ambient temperature. Both T_{exh} and

T_{room} are directly measured, while the experiments conducted at SUN did not include measurement of exhaust gases mass flow rate and composition; as a consequence, $\dot{m}_{exh}$ is determined by assuming the following stoichiometric methane combustion:



This reaction assumes that AISIN SEIKI unit is fuelled by methane instead of natural gas; however, since natural gas is mostly methane, we neglected the presence of the other compounds specified in Table 5. By assuming the measured natural gas mass flow rate equal to the methane mass flow rate and by knowing the molar mass of the reactants and the products in Eq. (24), both the mass flow rate and the composition of exhaust gases can be derived; based on the exhaust gases composition so determined (72.5% of N₂, 15.1% of CO₂ and 12.4% of H₂O as mass fractions), the calculation of $c_{p,exh}$ has been obtained as the mass-weighted mean of the products of the complete stoichiometric combustion reaction of methane calculated by using the software REFPROP [43] accordingly to the measured exhaust gases temperature.

Fig. 4 shows that during the time variation of the electrical demand and the cooling water flow rate is negligible, while cooling fluid inlet temperature is slowly increasing. No significant differences can be highlighted among the trends registered while test number 6 was running and the trends recorded during the other tests; as a consequence, time variation of the parameters q_{gross} , P_{net} , q_{gen} , $\dot{V}_{cw}$ and $T_{cw,i}$ reported in Fig. 4 is also representative of all tests described in Table 6. Due to the fact that the temperature of water entering the micro-cogeneration device for thermal load extraction was not really constant, the influence of both electrical output and coolant inlet temperature on both electrical and thermal efficiency has been estimated by:

- calculating the electrical and thermal efficiency values achieved every second during the experiments described in Table 6 by using the following formulae:

$$\eta_e = P_{\text{net}}/q_{\text{gross}} \quad (26)$$

$$\eta_q = q_{\text{gen}}/q_{\text{gross}} \quad (27)$$

- subdividing the entire duration of each test into several 3 min long time intervals where the coolant inlet temperature was varying in the range of $\pm 0.3^\circ\text{C}$ of the average value;
- calculating the average coolant inlet temperature $T_{\text{cw,i,mean}}$, the average net electrical output $P_{\text{net,ss,mean}}$, the average electric efficiency $\eta_{e,\text{mean}}$ and the average thermal efficiency $\eta_{q,\text{mean}}$; the average values have been calculating over the duration of each above defined 3 min long time intervals:

$$-T_{\text{cw,i,mean}} = \sum_N T_{\text{cw,i}}/N \quad (28)$$

$$-P_{\text{net,ss,mean}} = \sum_N P_{\text{net}}/N \quad (29)$$

$$-\eta_{e,\text{mean}} = \sum_N \eta_e/N \quad (30)$$

$$-\eta_{q,\text{mean}} = \sum_N \eta_q/N \quad (31)$$

where N is the experimental measurement acquired during each 3 min long time interval (i.e. $N = 180$).

In Figs. 5 and 6, respectively, the values of $\eta_{e,\text{mean}}$ (defined by Eq. (30)) and $\eta_{q,\text{mean}}$ (defined by Eq. (31)) are plotted as a function of the $T_{\text{cw,i,mean}}$ (defined by Eq. (28)).

In Figs. 5 and 6 the experimental points characterized by the same electric output, but different cooling water flow rate is highlighted by same colour of the symbols, but with different replenishment: empty symbols characterize the experiments performed with $\dot{V}_{\text{cw}} = 0.291/\text{s}$ (tests number 1–3), while the data measured while $\dot{V}_{\text{cw}}$ was equal to $0.181/\text{s}$ (tests number 4–6) are identified by using solid symbols.

Figs. 5 and 6 allow to analyse the influence of the temperature of the water entering the micro-cogeneration device, the electrical power output and the flow rate of cooling water on both electrical efficiency and thermal efficiency.

The analysis of this data indicates that there is a negligible influence of the coolant temperature or flow rate on either the electrical or thermal efficiencies. As a consequence, the coefficients a_3 – a_{26} (Eq. (5)) and b_3 – b_{26} (Eq. (6)) can be set to zero for the reasons explained earlier.

From both Figs. 5 and 6 it can be derived that both electrical and thermal efficiencies are affected by only the electrical power output: in particular, the experimental results showed that, whatever the cooling fluid temperature and flow rate, $\eta_{e,\text{mean}}$ rises with increasing the electrical power, while $\eta_{q,\text{mean}}$ increases at decreasing the electric output.

In Fig. 7 the average values of $\eta_{e,\text{mean}}$ and $\eta_{q,\text{mean}}$ corresponding to each value of the net electrical output experimentally investigated ($\approx 5.6 \text{ kW}$, $\approx 3.1 \text{ kW}$, $\approx 0.6 \text{ kW}$) are plotted as a function of the net electrical output.

This figure reports also the values of the coefficients a_0 , a_1 , a_2 (Eq. (5)) and b_0 , b_1 , b_2 (Eq. (6)) derived from a second order polynomial regression of the experimental results. Therefore the following values have been identified for the remaining coefficients of the model's electrical and thermal efficiency equations:

- $a_0 = 0.0361$
- $a_1 = -4.3890 \exp^{-9}$
- $a_2 = 6.6907 \exp^{-5}$
- $b_0 = 0.9368$
- $b_1 = 4.4399 \exp^{-9}$
- $b_2 = -6.9417 \exp^{-5}$

4.1.6. Calibration parameter 30

When inactive, the AISIN SEIKI cogeneration unit consumes some electricity. The electrical consumption during standby operation has been measured during the experiments described in

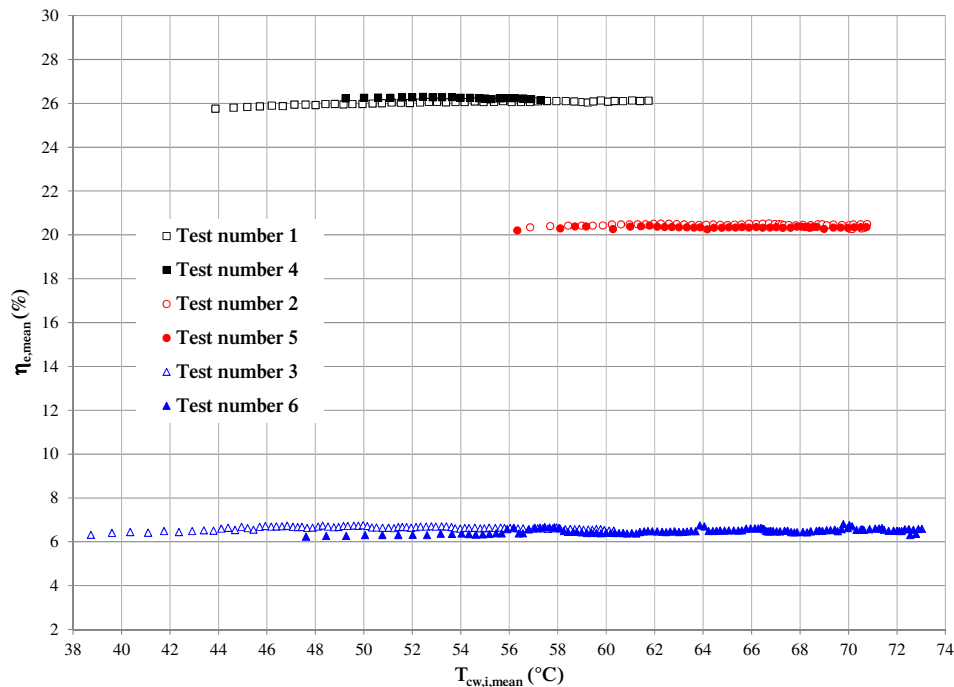


Fig. 5. Experimental values of $\eta_{e,\text{mean}}$ measured during tests number 1–6.

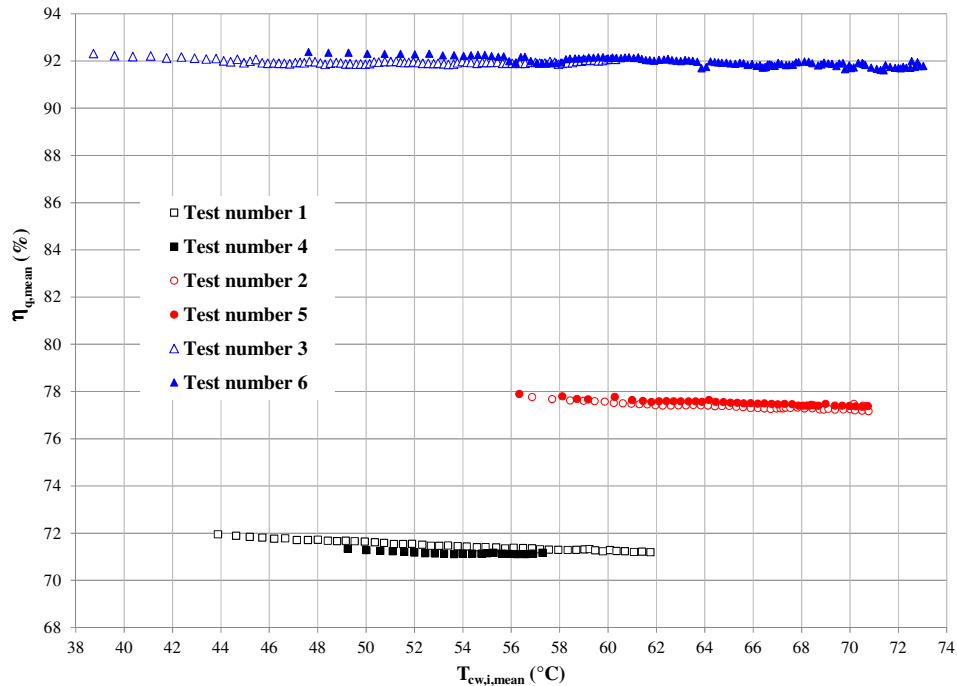


Fig. 6. Experimental values of $\eta_{q,mean}$ measured during tests number 1-6.

Table 6. At any case it has been observed that the standby power consumption is constant and equal to 90.0 W. Therefore, the model's net standby power generation (parameter 30) was set to -90.0 W.

4.1.7. Calibration parameters 27-29

The model provides two cool-down configurations:

- in “Mandatory cool-down mode” (calibration parameter 28 set to the value 1), the unit cannot be reactivated during the cool-down period;

- in “Optional cool-down mode”, the unit can be reactivated at any time during the cool-down period by applying a sufficient electric load.

The AISIN SEIKI cogeneration model can be reactivated during cool-down operation: as consequence, calibration parameter 28 was set to 2. In order to characterize cool-down operation, the Annex 42 model requires to identify also the cool-down period duration (calibration parameter 27) and the electric output during cool-down (calibration parameter 29).

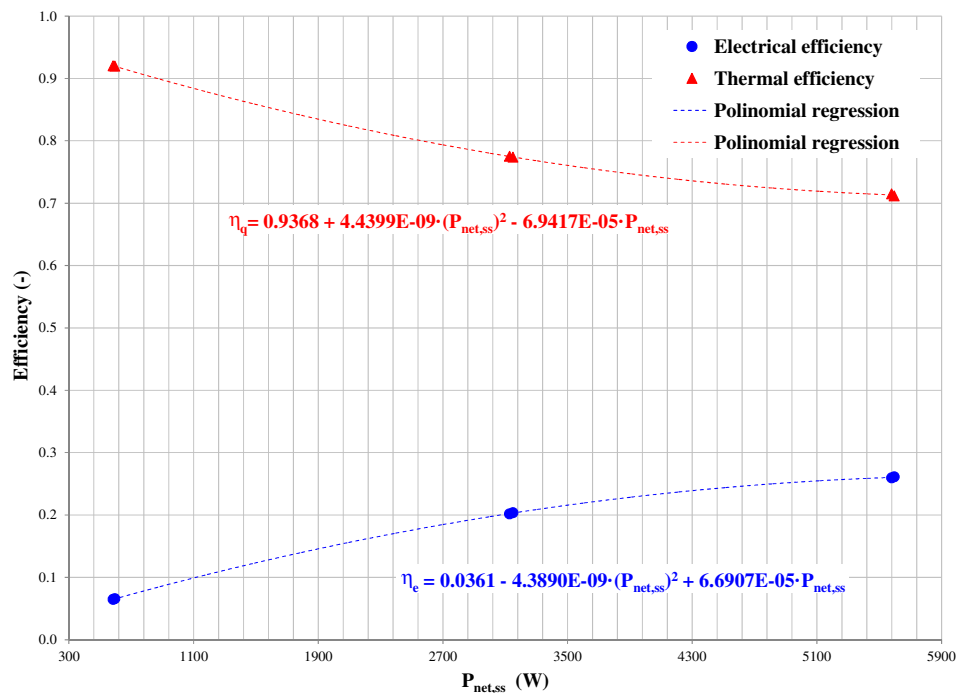


Fig. 7. Average values of $\eta_{e,mean}$ and $\eta_{q,mean}$ as a function of $P_{net,ss}$.

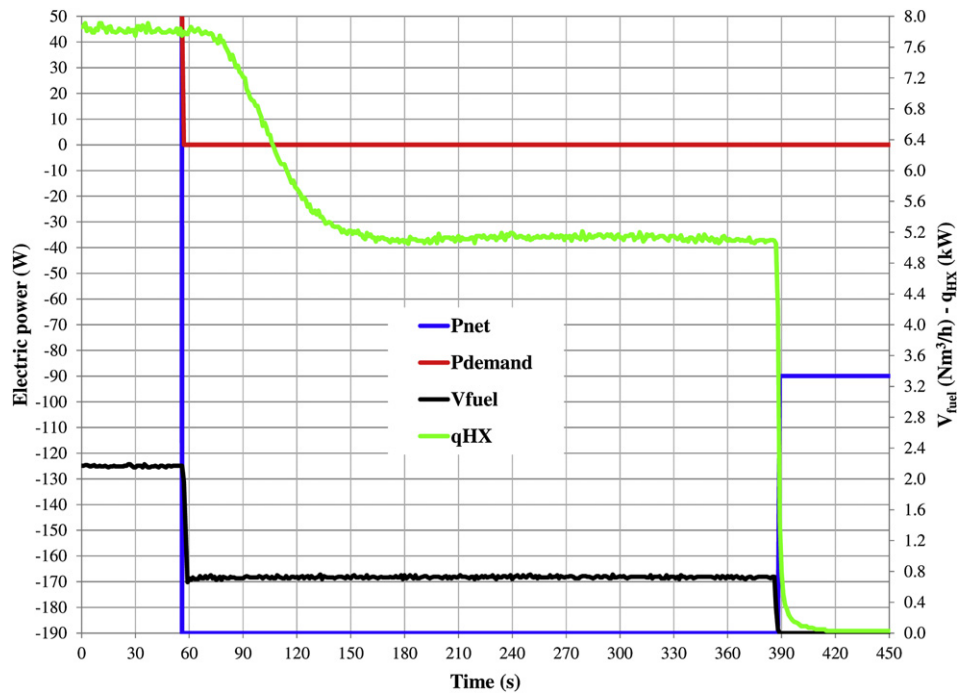


Fig. 8. System operation during cool-down mode.

Fig. 8 depicts the electric load applied to the MCHP system, the electric power consumed by the cogeneration device and the natural gas flow rate as a function of the time spent in cool-down mode.

This figure shows that till to 60 s from the beginning of the test the electric demand is around 6.7 kW and the MCHP system was operating in normal mode at the operating condition specified for the test number 1 (Table 6); then the electric load applied to the MCHP device is switched off and the cool-down period begins; during cool-down operation:

1. the engine runs with a lower revolution speed in comparison to the steady-state operation;
2. the cogenerator consumes 190.0 W as electric power;
3. the fuel flow rate drops till a constant value equal to around $0.7 \text{ Nm}^3/\text{h}$;
4. the thermal power recovered from the water–glycol mixture becomes less and less relevant converging towards around 5.2 kW.

When cool-down operation stops the engine consumes no fuel, the thermal power provided by the MCHP system converges rapidly towards zero and the cogeneration device returns into stand-by mode.

According to the measured data reported in Fig. 8, cool-down duration is 331 s. The same cool-down duration has been measured also at the end of the other tests described in Table 6 and, therefore, in this work the parameter 27 is set to 331 s; parameter 29 (electric consumption during cool-down) is set to -190.0 W .

However some discrepancies can be highlighted in relation to the cool-down mode by comparing the Annex 42 model specification and the real operation of AISIN SEIKI cogeneration device. In fact the model assumes that during cool-down the engine consumes no fuel and generates no heat; these assumptions are clearly in contrast with the experimental behaviour of the AISIN SEIKI system. In addition it can be highlighted that in case of the end-user requires the unit activation during cool-down (i.e. the electric load becomes higher than 300 W), the Annex 42 assumes

that the MCHP system switches from cool-down mode to warm-up mode and, then, to normal mode. Differently from Annex 42 model assumption, the AISI SEIKI unit switches directly from cool-down mode to normal mode (by-passing the warm-up mode) in case of an electric load higher than 300 W is requested during cool-down operation. These experimental observations highlight that Annex 42 model is not able to fully follow the experimental operation of the AISIN SEIKI cogeneration system during cool-down operation: as a consequence, some improvements to the structure of the model should be considered in order to better predict the experimental operation of the unit during cool-down.

4.1.8. Calibration parameter 26

In the Annex 42 model, the warm-up is the period during which there is a static time delay between activation of the unit and electrical power generation and, therefore, the warm-up period starts when the electric load is applied and finishes when net electric output generation starts. In order to identify the duration of warm-up period (calibration parameter 26), tests number 1–6 described in Table 6 have been analysed. Fig. 9 plots the electric demand, the electric output provided by the cogeneration device and the natural gas flow rate as a function of the time spent in operation. The data reported in this figure are referred to the test number 1 described in Table 1 for a cold start-up (unit shut-down for one week before the experiment was performed).

At the beginning of the test, no electric output is requested: as a consequence the system is in stand-by mode. During stand-by operation the electronic controllers within the unit require an electric power equal to 90.0 W while awaiting activation.

After around 30 s the electric demand passes from zero to around 6.7 kW and, therefore, the unit starts operating by activating the fan dedicated to the inverter cooling: due to fan operation the electric power consumed by the MCHP system increases, passing from 90.0 W (stand-by period) to 190.0 W. As can be derived from Fig. 9, the electric power generation does not start when the electric load is applied: the cogeneration unit starts providing electric power 91 s after the request of the electric output.

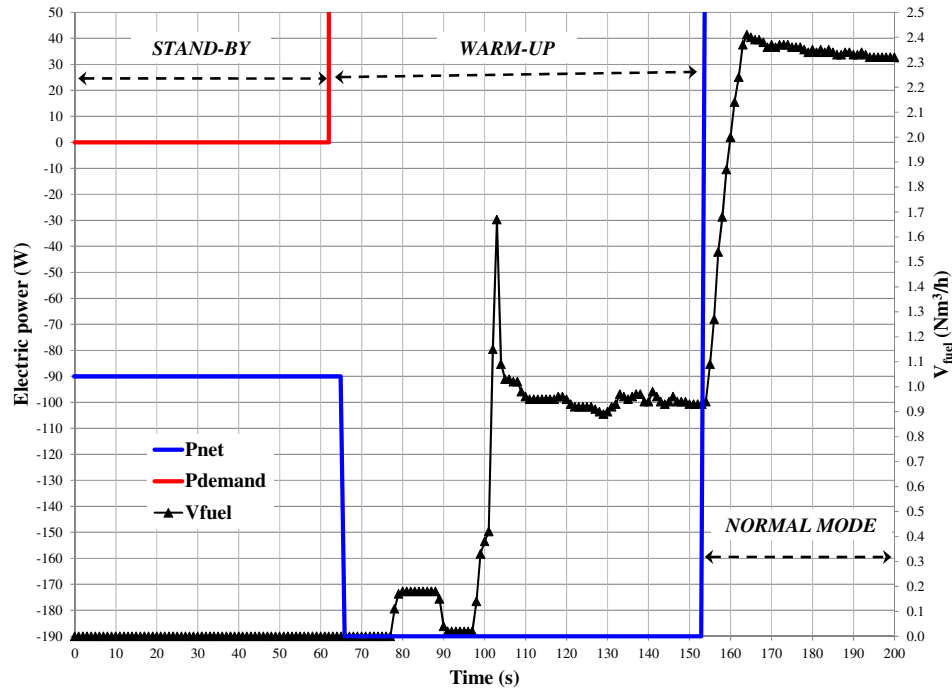


Fig. 9. Transition from standby mode to normal mode during test number 1 in case of cold start-up.

By analysing the trend of the fuel flow rate, it can be noticed that the MCHP system does not start at the first tentative: this is probably due to the fact that the engine did not yet reach its operational temperature at the first tentative. At second starting tentative the unit starts: natural gas flow rate remains relatively constant at around 0.9–1.0 Nm³/h till the warm-up period ends and then $\dot{V}_{\text{fuel}}$ converges towards its steady-state value.

In the Annex 42 model the start-up characteristics of internal combustion engines are considered not sensitive to the engine temperature. In order to verify the reliability of this hypothesis, at the end of the test number 1 described in Table 6 the unit has been restarted after cool-down by applying exactly the same operating conditions of the above-mentioned test number 1. In case of this warm start-up (unit restarted just after around 4 h of unit operation at the maximum electric load) the unit started at the first tentative and the warm-up duration (62 s) has been considerably different from the warm-up duration measured in case of cold start-up. Warm-up duration has been measured also during the remaining test number 2–6 specified in Table 6: the results of these measurements are reported in Table 7.

The data reported in Table 7 mean that warm-up duration is significantly affected by the engine temperature that in turn depends on ambient temperature, operation time and electric load applied to the unit before the starting. However Annex 42 model does not allow to take into account this influence: as a consequence, improvements to the structure of the model should be proposed based upon these experimental observations. In this

work the higher warm-up duration experimentally determined (129 s) was set for the parameter 26.

4.1.9. Calibration parameters 20–21

As explained in Section 2, the Annex 42 model allows constraints on the maximum rate of change permitted in the system fuel flow (calibration parameter 20); the user may optionally constrain the unit's predicted dynamic electric response (calibration parameter 21) using empirical data using a linear derivative. Eq. (11) defines calibration parameter 20, while Eq. (13) defines calibration parameter 21.

A specific test has been performed in order to identify the values of both parameters 20 and 21 and the results of this experiment are reported in Fig. 10: this figure plots the electric load requested to the cogeneration device P_{demand} , the net electric power provided by the MCHP to the end-user P_{net} and the natural gas flow rate $\dot{m}_{\text{fuel}}$ as a function of the time while the system is switching from warm-up mode to normal mode.

The electric demand is maintained as constant throughout the test; at the beginning the unit is in warm-up mode; after around 12 s the MCHP system starts supplying electric power and fuel consumption becomes more and more relevant till both electric output and natural gas flow rate converge towards a relatively constant value.

The values of both $d\dot{m}_{\text{fuel}}/dt$ (black dotted line) and dP_{net}/dt (blue solid line) related to above-specified test are depicted in Fig. 11.

The parameter $d\dot{m}_{\text{fuel}}/dt$ reported in this figure has been derived from the measured volumetric fuel flow rate by calculating the natural gas density at normal temperature and pressure conditions as follows:

$$\rho_{\text{fuel}} = (P_n \cdot MM) / (R \cdot T_n) = (101.325 \cdot 16.123) / (8.3145 \cdot 273.15) = 0.719 \text{ kg/Nm}^3$$

In calculating ρ_{fuel} , natural gas has been assumed as an ideal gas and its molar mass MM has been calculated by considering the composition specified in Table 5.

Table 7
Warm-up durations.

Test number	Warm-up duration (s)	Comments
1	62	Warm start-up
1	91	Cold start-up
2	101	Cold start-up
3	121	Cold start-up
4	118	Cold start-up
5	129	Cold start-up
6	107	Cold start-up

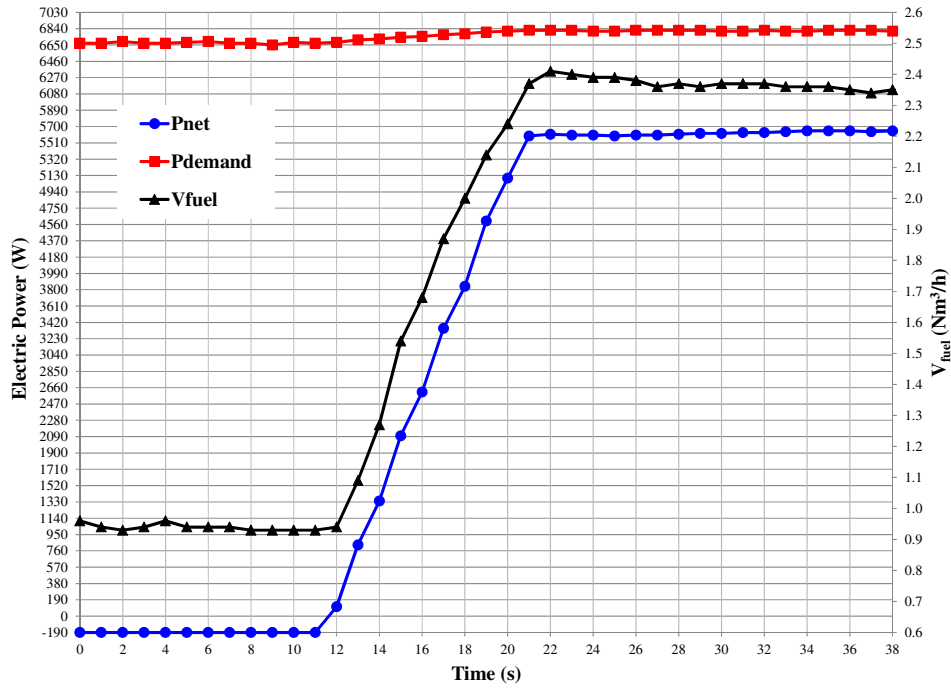


Fig. 10. P_{net} , P_{demand} and $\dot{m}_{fuel}$ as a function of time.

From the above-mentioned experimental test the following values of calibration parameters 20 and 21 have been derived:

$$\left. \frac{d\dot{m}_{fuel}}{dt} \right|_{\max} = 5.4 \exp^{-5} \text{ kg/s}^2;$$

$$\left. \frac{dP_{net}}{dt} \right|_{\max} = 760.0 \text{ W/s}.$$

4.1.10. Calibration parameters 91–100

Calibration parameter 91 defines the cooling loop configuration: the AISIN SEIKI unit is incapable of regulating the flow rate of

water–glycol mixture. Therefore, the cooling loop configuration was set to external pump. In this configuration, the water–glycol mixture flow correlation coefficients described in the model specification (calibration parameters 92–100) are superfluous.

4.1.11. Calibration parameters 101–103

In the micro-cogeneration systems the air stoichiometry is regulated to manage the combined heat and power unit's combustion efficiency: in the Annex 42 model the air flow rate is calculated using a second order polynomial function based on the fuel mass flow rate. The experiments conducted at SUN did not

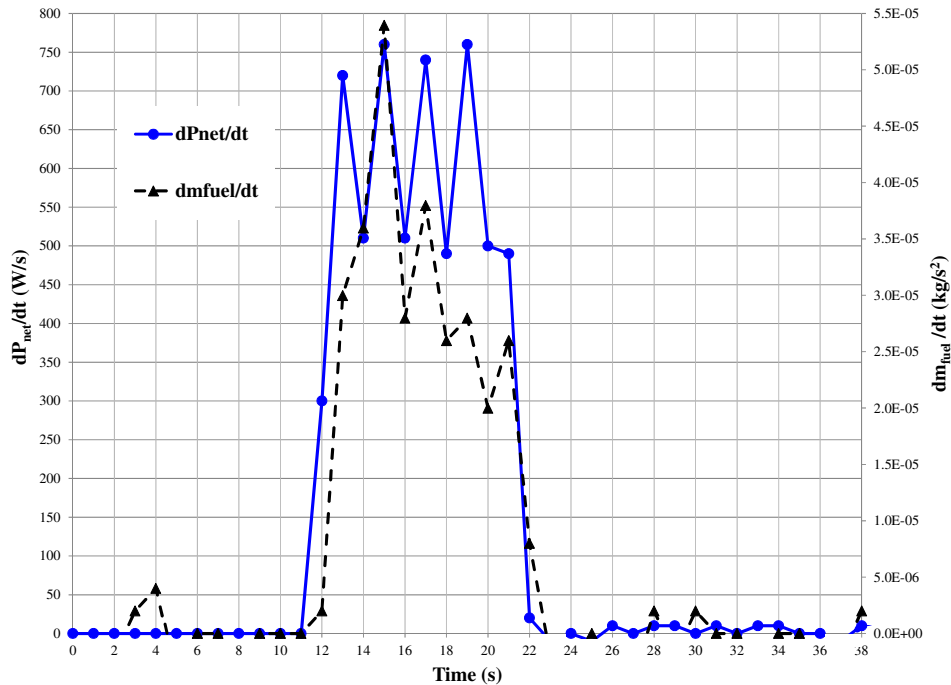


Fig. 11. dP_{net}/dt and $d\dot{m}_{fuel}/dt$ as a function of time.

include measurement of supply air flow rate. Without these data, calibration of the model's air flow correlations is impossible. As a consequence, the combustion air flow correlation coefficients (calibration parameters 101–103) were set to zero during the model calibration.

4.2. Dynamic model calibration

The second stage of the calibration process was to tune the characteristics ($[MC]_{eng}$, $[MC]_{cw}$, $[UA]_{Hx}$, and $[UA]_{loss}$) of the dynamic thermal model using data from dynamic tests on the micro-CHP unit; these tests could cover periods when the unit is in start-up or shut-down mode and/or when the thermal or electrical load on the unit is changed.

4.2.1. Calibration parameters 22–25

Because the SUN experiments did not include sufficient measurements to directly calibrate all of the inputs required by the model, an iterative dynamic parameter identification approach was adopted. This approach uses the GENOPT software tool and a simplex-search-based approach to determine the set of the model's dynamic parameters UA_{loss} , UA_{Hx} , $[MC]_{cw}$ and $[MC]_{eng}$ providing the closest agreement to the experimental data.

GENOPT drove the simulation software incorporating the cogeneration device model (in this case TRNSYS 16 [33]) over multiple simulations. In these simulations:

1. the model was subjected to the same cooling water temperature, cooling water flow rate, electric power generation and ambient temperature, as the AISIN SEIKI unit testes at SUN;
2. a set of tentative values was chosen for the calibration parameters 22–25;
3. the optimization utility invokes the building simulation program, which performs a simulation using the parameters described in the input files and the boundary conditions described in the SUN data;
4. at the end of each simulation, the model's predicted outlet temperature $T_{cw,o,pred}$ was extracted from the simulation and compared to the experimental value $T_{cw,o,exp}$ each time step. The objective of this process was to minimise the mean square error between these two values over the N time steps of the simulation:

$$\varepsilon = \sum_N (T_{cw,o,pred} - T_{cw,o,exp})^2 / N \quad (32)$$

The coolant outlet temperature was used as the target for the optimisation as it is the principle, coupling variable between the generic cogeneration model and the systems model into which it would be integrated;

5. the values assigned to the parameters 22–25 were adjusted based on the results of the simulation according to the selected optimization algorithm and steps 2–4 were repeated until the best-possible agreement between model outputs and empirical data was achieved.

GENOPT automates steps 2–4 of the parameter identification process, and can perform thousands of simulations while searching for the optimal input set.

The dataset used in the calibration process was derived from the test number 1 described in Table 6, with measurements taken at a frequency of 1 s. The data used in the dynamic calibration

includes a warm-up of the engine from cold till the radiator fan activation.

The parameter values derived during dynamic calibration of the Annex 42 combustion cogeneration model are reported in the following:

- $UA_{loss} = 58.0 \text{ W/K}$
- $UA_{Hx} = 3493.0 \text{ W/K}$
- $[MC]_{cw} = 7955.0 \text{ J/K}$
- $[MC]_{eng} = 82,845.0 \text{ J/K}$

While these values provide the best agreement between the model predictions and the measurements in the SUN data subset, care must be taken in their use and interpretation. The parameter optimization procedure determined four parameters using only one criteria to evaluate the suitability of the parameter set. Thus, there may exist multiple sets of parameter inputs that provide the same result, and the set chosen by the parameter optimization procedure may not be the best representation of the actual AISIN SEIKI unit used in the SUN tests.

With the model as currently configured, it was assumed that heat transfer characteristics of the heat exchanger are constant over the operating temperature range of the unit. However this assumption with regards to replicating the dynamic performance of the calibrated unit was small due to the fact that the AISIN SEIKI system by-passes totally or partially the water–glycol mass flow rate into the radiator and activates the radiator fan depending on the water–glycol temperature at the inlet of the plate heat exchanger.

4.3. Model validation

After the calibration activity, an empirical validation was then used to assess the validity of the mathematical models to simulate the performance of the cogeneration device through the comparison of simulation results with measurements taken in laboratory from an experimental test completely disjunct from the tests used to calibrate the Annex 42 model. This model validation has been carried out not only to verify the mathematical model, but also the accuracy of its calibration using the empirical data gathered from the calibration experiments.

The data used to validate the model have been measured by operating the system in order to follow the electricity demand profile during cold season derived by Sasso et al. [44] from a Report of the Politecnico of Milano based on measurements onsite of the electric consumptions in the Italian residential sector within the SAVE EURECO and MICENE projects [45]. The report provides 10-min data for:

- ✓ 110 flats located in 5 Italian regions analysed for 3 years;
- ✓ the monitored electrical energy consumption and electric power demand of the total household appliances and lighting systems;
- ✓ electric energy consumption and electric power demand of each flat and of the whole building.

The data provided describe the total electricity demand values, including the demand of appliances (refrigerator, standby loads of electronics, lighting, household appliances, and IT devices), but exclude any demand for electric heating.

In Fig. 12 the electric load profile for a 5-dwelling Medium Family House (MFH) electricity demand profile during cold season derived from Ref. [44] is reported (dotted red line); given the constraints of the experimental set-up in controlling the electric demand, the AISIN SEIKI unit has been experimentally operated in

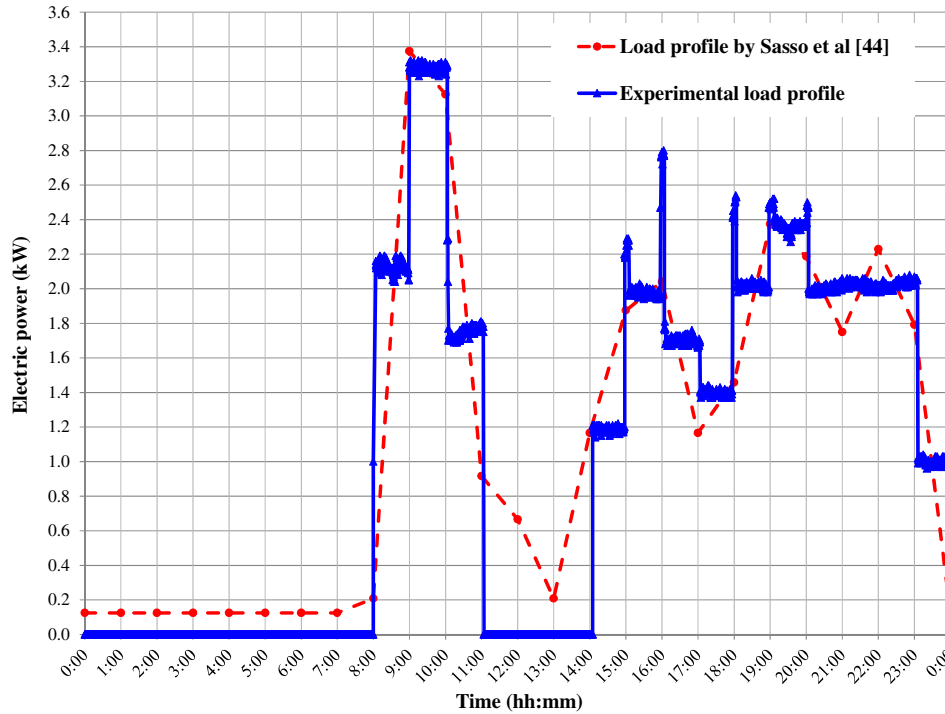


Fig. 12. Southern Italy cold season daily electricity profile for 5 dwellings [44].

electric load following control strategy to respond to the electric load profile depicted in Fig. 12 as solid blue line. The experimental test has been performed the 6th of April 2011. This experiment has been simulated by means of the Annex 42 model by using the measured values as inputs.

Figs. 13 and 14 plot the correlation between the model predictions and experimental values of primary power q_{gross} and heat recovery q_{HX} : regarding the data reported in these plots, it can be noticed that a lower heating value equal to 49,599 kJ/kg has been

assumed in calculating $q_{\text{gross,exp}}$ while a simulation time step equal to 1 s has been considered in carrying out the simulation with TRNSYS. In these figures the difference between the predicted and measured values is also reported in order to better highlight where are located the main deviations between the simulation and the experimental results.

The accuracy of the calibration was validated by using the following metrics quantifying both the instantaneous and cumulative difference in the model predictions:

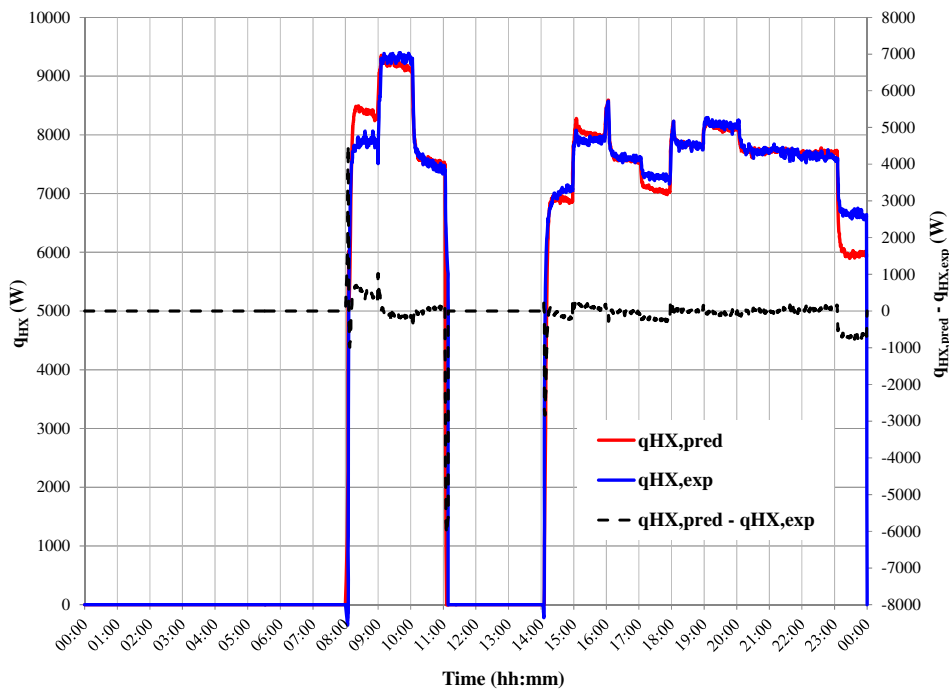


Fig. 13. Comparison of predicted and measured values of heat recovery.

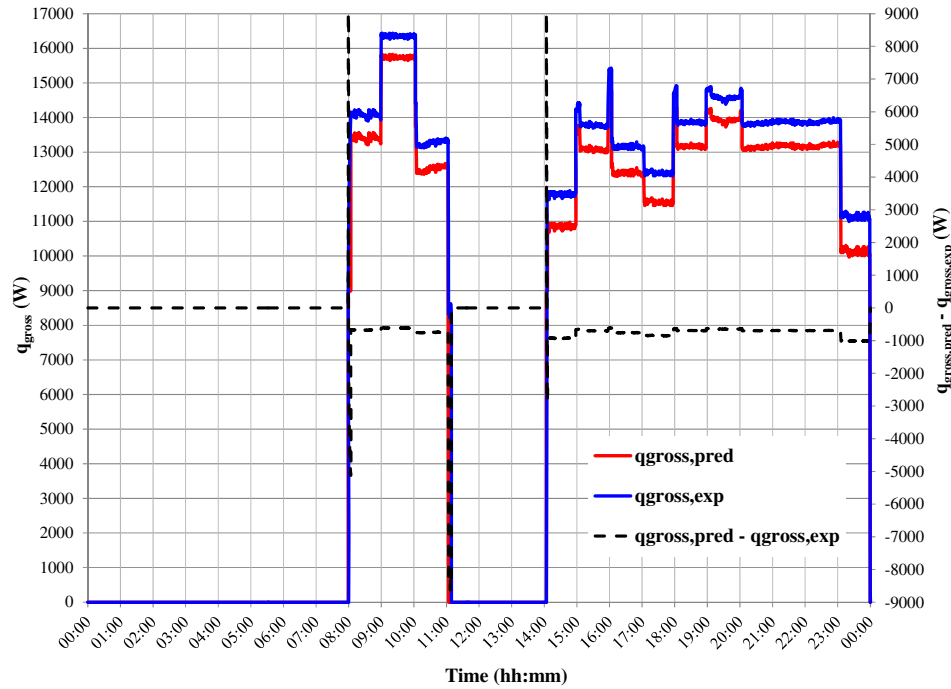


Fig. 14. Comparison of predicted and measured values of primary power.

- the average error $\bar{\varepsilon}$;
- the average absolute error $|\bar{\varepsilon}|$;
- the root mean square error ε_{RMS} ;
- the cumulative error in the energy prediction ε_E .

These parameters are defined as follows:

$$\varepsilon_i = g_{\text{pred},i} - g_{\text{exp},i} \quad (33)$$

$$\bar{\varepsilon} = \sum_{i=1}^N \varepsilon_i / N \quad (34)$$

$$|\bar{\varepsilon}| = \sum_{i=1}^N |\varepsilon_i| / N \quad (35)$$

$$\varepsilon_{\text{RMS}} = \sqrt{\sum_{i=1}^N (\varepsilon_i - \bar{\varepsilon})^2 / N} \quad (36)$$

$$\varepsilon_E = (E_{\text{pred}} - E_{\text{exp}}) / E_{\text{pred}} \quad (37)$$

where:

- $g_{\text{pred},i}$ is the measured value at time step i ;
- $g_{\text{exp},i}$ is the predicted value, at time step i ;
- N is the number of measurements.

The statistical comparison among experimental and predicted results has been performed not only in relation to the entire database, but also by segregating the data by system mode operation (stand-by mode, cool-down mode, warm-up mode, steady-state mode) with the aim to highlight both strong points and the faults of the model.

The whole database consists of 2875 points; the most part (1548) of the experimental values have been measured during

steady-state operation; only few points have been recorded during cool-down and warm-up operation.

Table 8 summarizes the errors between the model predictions and observations from the calibration data set.

With reference to the whole database the predicted electric output agrees very well with experimental observations; the Annex 42 model tends to underpredict both heat recovery and primary power consumption, even if the prediction of q_{gross} exhibits more variation between measurements and predicted values. However, at the end of the simulation, the predicted cumulative heat recovery differs from their measured values by 1.0%, while the cumulative gross input is predicted with a percentage error equal to 6.1%.

Table 8

Comparison of Annex 42 combustion cogeneration model predictions with SUN data.

	Number of experimental points	Parameter	$\bar{\varepsilon}$ (W)	$ \bar{\varepsilon} $ (W)	ε_{RMS} (W)	ε_E (%)
Whole database	2875	Q_{Hx}	−41.4	116.8	424.6	−
		Q_{gross}	−423.5	442.3	700.1	−
		P_{net}	−1.8	2.4	55.0	−
		E_{Hx}	−	−	−	−1.0
		E_{gross}	−	−	−	−6.1
		E_{net}	−	−	−	−0.2
Standby mode	1309	Q_{Hx}	0.0	0.0	0.0	−
		Q_{gross}	0.0	0.0	0.0	−
		P_{net}	−0.4	0.4	6.2	−
Cool-down mode	11	Q_{Hx}	−5361.5	5361.5	5396.4	−
		Q_{gross}	−8402.1	8402.1	7979.8	−
		P_{net}	0	0	1.8	−
Warm-up mode	7	Q_{Hx}	295.2	309.1	709.3	−
		Q_{gross}	733.7	4436.1	5538.4	−
		P_{net}	−712.9	875.7	1108.3	−
Steady-state	1548	Q_{Hx}	−40.2	177.3	352.4	−
		Q_{gross}	−730.1	741.7	409.1	−
		P_{net}	0.1	0.1	5.2	−

As can be derived from Table 8, the main deviations between the measured and predicted results correspond to the cool-down period of the unit and indicate that, as highlighted in Section 3, the Annex 42 model significantly underpredicts both the primary power consumption (Annex 42 model assumes no fuel consumption during cool-down, while 2772.7 kJ have been measured as primary energy consumption during cool-down) and the thermal recovery (Annex 42 model assumes no heat generation during cool-down, while 2039.5 kJ have been derived from the experimental data as thermal energy provided during cool-down). The differences between the measured and predicted values are also explained by taking into account the wrong estimation of warm-up duration by Annex 42 model due to the fact that Annex 42 model does not allow to consider the influence of the ambient temperature, operation time and electric load applied to the unit before warm-up period starting. No significant discrepancies can be highlighted between the experiment and the simulation by considering the data recorded during standby operation.

The reasons for the discrepancy in the heat recovery also reflect the Annex 42 assumption of heat transfer characteristics of the heat exchangers constant over the operating temperature range of the unit.

Even if in the future it would be desirable to extend this work to consider other operating scenarios and despite some problems identified mainly during cool-down and start-up, the results of the empirical validation allow to conclude that the model is able to predict the thermal and electric behaviour of the AISIN SEIKI unit and, therefore, a detailed performance assessment can now be performed using this calibrated model to examine the applicability of this device for supplying building electrical and thermal energy requirements.

5. Conclusions

The International Energy Agency approved the formulation of a new research annex (Annex 42) under the Energy conservation in Builds and Community Systems (ECBCS) implementing agreement. Annex 42 developed two generic models that characterize the thermal and energy performance of micro-cogeneration devices suitable for use in whole building simulation programs: one for fuel cell-based cogeneration systems (SOFC and PEMFC) and a second one for combustion-based systems (SE and ICE).

In this study, the Annex 42 combustion-based cogeneration model was experimentally calibrated and validated using data collected from an AISIN SEIKI cogeneration unit at Seconda Università degli studi di Napoli (SUN).

The experimental procedures that were employed to calibrate the Annex 42 model were described in detail and the results of this calibration approach were presented. During the calibration activity, some discrepancies between the structure of the models and the experimental behaviour of the micro-cogeneration unit have been highlighted and, therefore, some modifications to the mathematical form of the Annex 42 have been suggested.

The calibrated inputs derived in the current study were used in an empirical validation effort. In order to empirically validate the model, an additional experiment (disjunct from the tests used to calibrate the model) was conducted and the results of the validation activity were reported.

The calibrated model exhibits reasonable agreement when compared with the validation data set: the predicted fuel use, electric output and heat recovery over the duration of the data set all differed from observed values by -6.1% , -0.2% and -1.0% , respectively. As a consequence, despite some discrepancies between the predictions and the experimental results mainly during cool-down and warm-up operation, it can be concluded that the model gives an accurate representation of the unit's dynamic and steady-state performance.

Although this empirical validation builds confidence in the Annex 42 models, in the future it would be desirable to extend this work to consider other operating scenarios, mainly load profiles characterized by frequent on–off operation. Future research will apply the calibrated model to examine the thermal and electrical performance of the AISIN SEIKI cogeneration unit in various residential buildings, in various climates, and under various operating scenarios to contrast the performance of the technology to conventional heating and electrical supply systems.

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Nomenclature

Latin letters

c_p : specific heat at constant pressure (kJ/kg K)
 E : energy (J)
 ICE : internal combustion engine
 LHV : lower heating value (kJ/kg)
 $\dot{m}$: mass flow rate (kg/s)
 MM : molar mass (g/mol)
 $MCHP$: micro combined heat and power generation
 MFH : medium family house
 p : pressure (kPa)
 P_{demand} : electric power demand (kW)
 P_{net} : electric power output (kW)
 q : thermal power (kW)
 q_{gross} : primary power (kW)
 q_{HX} : recovered heat (kW)
 q_{gen} : recoverable heat (kW)
 R : universal gas constant (kJ/kmol K)
 SFH : small family house
 SME : medium scale enterprises
 SE : Stirling engine
 $SOFC$: solid-oxide fuel cell
 V : volumetric flow rate (m³/h)
 t : time (s)
 T : temperature (°C)

Greeks

ϵ : cumulative error (%)
 $\bar{\epsilon}$: average error (W)
 $|\bar{\epsilon}|$: average absolute error (W)
 ϵ_{RMS} : root mean square error (W)
 η : efficiency (–)
 ρ : density (kg/m³)

Subscripts

cw : cooling water
 e : electric
 eng : engine
 exh : exhaust gases
 exp : experimental
 $fuel$: natural gas
 HWT : hot water tank
 i : inlet
 max : maximum
 $mean$: average
 min : minimum
 n : normal conditions (0 °C, 101.325 kN/m²)
 o : outlet
 $pred$: predicted
 q : thermal
 $room$: external
 ss : steady-state